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Authors

Brown, Austin L.
Sperling, Daniel
Austin, Bernadette
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7. Author(s)
Austin L. Brown, orcid.org/0000-0002-5454-1465; Daniel Sperling, orcid.org/0000-0002-8744-7651; Bernadette Austin, orcid.org/0000-0001-8729-853X; JR DeShazo, orcid.org/0000-0002-7997-6422; Lew Fulton, orcid.org/0000-0001-8292-3420; Timothy Lipman; Colin Murphy, orcid.org/0000-0001-8615-9466; Jean Daniel Saphores, orcid.org/0000-0001-9514-0994; Gil Tal, orcid.org/0000-0001-7843-3664; Carolyn Abrams; Debapriya Chakraborty, orcid.org/0000-0001-9898-4068; Daniel Coffee; Sina Dabag, orcid.org/0000-0002-5717-4197; Adam Davis, orcid.org/0000-0001-6324-6380; Mark A Delucchi; Kelly L. Fleming, orcid.org/0000-0002-7249-843X; Kate Forest, orcid.org/0000-0001-6375-1299; Juan Carlos Garcia Sanchez, orcid.org/0000-0002-1684-5847; Susan Handy, orcid.org/0000-0002-4141-1290; Michael Hyland, orcid.org/0000-0001-8394-8064; Alan Jenn, orcid.org/0000-0003-4232-0697; Seth Karten; Blake Lane, orcid.org/0000-0002-6299-8326; Michael Mackinnon, orcid.org/0000-0002-6837-3861; Elliot Martin, orcid.org/0000-0001-5889-5781; Marshall Miller, orcid.org/0000-0002-9105-3188; Monica Ramirez-Ibarra, orcid.org/0000-0002-1736-8069; Stephen Ritchie, orcid.org/0000-0001-7881-0415; Sara Schremmer, orcid.org/0000-0001-7402-5698; Joshua Segui; Susan Shaheen, orcid.org/0000-0002-3350-856X; Andre Tok, orcid.org/0000-0002-0387-0170; Aditya Voleti; Julie Witcover, orcid.org/0000-0001-6184-1223; Allison Yang

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9. Performing Organization Name and Address

Institute of Transportation Studies, Davis
1605 Tilia Street, Davis, Ca 95616

Institute of Transportation Studies, Berkeley
109 McLaughlin Hall, MC1720, Berkeley, CA 94720-1720

Institute of Transportation Studies, UCLA
3320 Public Affairs Building, Los Angeles, CA 90095-1656

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16. Abstract

The purpose of this report is to provide a research-driven analysis of options that can put California on a pathway to achieve carbon-neutral transportation by 2045. The report comprises thirteen sections. Section 1 provides an overview of the major components of transportation systems and how those components interact. Section 2 discusses the impacts the COVID-19 pandemic has had on transportation. Section 3 discusses California’s current transportation-policy landscape. These three sections were previously published as a synthesis report. Section 4 analyzes the different carbon scenarios, focusing on “business as usual” (BAU) and Low Carbon (LC1). Section 5 provides an overview of key policy mechanisms to utilize in decarbonizing transportation. Section 6 is an analysis of the light-duty vehicle sector, section 7 is the medium- and heavy-duty vehicle sectors, section 8 is reducing and electrifying vehicle miles traveled, and section 9 is an analysis of transportation fuels and their lifecycle. The following sections are an analysis of external costs and benefits: section 10 analyzes the health impacts of decarbonizing transportation, section 11 analyzes equity and environmental justice, and section 12 analyzes workforce and labor impacts. Finally, future research needs are provided in section 13. The study overall finds that cost-effective pathways to carbon-neutral transportation in California exist, but that they will require significant acceleration in a wide variety of policies.

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Driving California's Transportation Emissions to Zero

April 2021

Authors:

Austin L. Brown[1], Daniel Sperling[1], Bernadette Austin[1], JR DeShazo[3], Lew Fulton[1], Timothy Lipman[2], Colin Murphy[1], Jean Daniel Saphores[4], Gil Tal[1]

Carolyn Abrams[1], Debapriya Chakraborty[1], Daniel Coffee[3], Sina Dabag[4], Adam Davis[1], Mark A Delucchi[1,2], Kelly L. Fleming[1], Kate Forest[4], Juan Carlos Garcia Sanchez[1], Susan Handy[1], Michael Hyland[4], Alan Jenn[1], Seth Karten[1], Blake Lane[4], Michael Mackinnon[4], Elliot Martin[2], Marshall Miller[1], Monica Ramirez-Ibarra[4], Stephen Ritchie[4], Sara Schremmer[1], Joshua Segui[3], Susan Shaheen[2], Andre Tok[4], Aditya Voleti[3], Julie Witcover[1], Allison Yang[3]

[1]UC Davis, [2]UC Berkeley, [3]UCLA, [4]UC Irvine

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Table of Contents

Table of Contents

Executive Summary..1

Study Goal 1

Priorities and Structure 1

Scenarios 2

Key Policies..6

Benefits and Impacts.. 15

Benchmarks.. 16

Conclusion 18

1 Background..20

1.1 Current Policy Context.. 20

1.2 Other Impacts and Externalities 30

2 Special Section: COVID-19 and Transportation..32

2.1 Impacts.. 32

3 Current State of the Transportation System 36

3.1 Transportation, the economy, and greenhouse gas emissions.. 36

3.2 Light-duty vehicles (LDVs).. 43

3.3 Heavy-duty vehicles (HDVs).. 58

3.4 Vehicle miles traveled (VMT).. 66

3.5 Fuels.. 92

3.6 Equity and Environmental Justice.. 100

3.7 Health.. 104

3.8 Labor and employment 112

4 Scenarios..129

4.1 Business-as-Usual Scenario.. 129

4.2 Low Carbon Scenarios.. 136

4.3 Fuels: Life Cycle Emissions.. 146

4.4 Benchmarking Milestones 154

4.5 Side Cases 155

4.6 Sensitivity Analysis.. 164

5 Policy Mechanisms 166

5.1 Milestones and Progress Tracking.. 167

5.2 Economy-wide policy.. 169

6 Light-duty Vehicle Electrification 171
6.1 Introduction 171
6.2 Scenarios 173
6.3 Discussion 194
6.4 Equity 194
6.5 Key Policies 196
6.6 5-Year Plan 197
6.7 Conclusions 200
7 Medium- and Heavy-Duty Vehicles 201
7.1 Trip Length Distribution Analysis 202
7.2 Achieving LC1 Targets for Specific Truck categories 206
7.3 Charging/Refueling Infrastructure 221
7.4 Overall Recommendations to Reach LC1 Targets 230
8 Vehicle-Miles Travelled 232
8.1 Introduction 232
8.2 Scenarios 238
8.3 Conclusion from VMT Reduction Analysis 253
9 Fuel Technology and Policy to Support a Carbon-Neutral Transportation System 254
9.1 Introduction 254
9.2 Scenarios 255
9.3 Implications of this Study for California’s Fuel Technology and Policy 263
9.4 Key Policies 265
9.5 Equity 279
10 Assessment of Health Impacts 281
10.1 Introduction 281
10.2 Approach 1: InMAP 281
10.3 Approach 2: CMAQ 293
10.4 Assessment of Health Impacts using BenMAP 304
11 Equity and Environmental Justice 311
11.1 Current Policy 311
11.2 Site Studies 320
12 Workforce Impacts and Relevant Policy Considerations 323
12.1 Introduction 323
12.2 Our Approach for Forecasting Workforce Trends 325
12.3 Model Background and Limitations 326

12.4 Forecasted Workforce Impacts ... 327
12.5 Sector-Specific Model Outputs and Policy Discussion ... 330
12.6 Conclusion ... 354
13 Future Research Needs ... 356
13.1 Public charging infrastructure ... 356
13.2 Ownership, use and safety of automated (autonomous) vehicles (AVs) ... 356
13.3 Freight efficiency and impacts ... 356
13.4 Strategies to reduce passenger VMT ... 356
13.5 Mobility and accessibility of physically and economically disadvantaged travelers ... 357
13.6 Vehicle purchase decisions are affected by many policies ... 357
13.7 Public finance of transportation ... 357
13.8 Costs and Performance of New Propulsion Technologies ... 357
13.9 Costs of Rapid Transitions ... 358
13.10 Production, Distribution and Use of Alternative Fuels ... 358
13.11 Integration of Transportation and Electric Systems ... 358
13.12 Transportation Systems Resilience ... 358
13.13 Labor and Employment Implications of a transition to ZEVs? ... 359
13.14 Evaluation and Cost-Effectiveness ... 359
14 Appendices ... 360
14.1 Light-duty Vehicle Appendix: TCO Calculation ... 360
14.2 VMT Appendix: VMT Topic Policy Scenario Descriptions ... 363
14.3 Fuel Appendix: Model Design and Methodology ... 389
14.4 Health Appendix: Health Impacts Analysis ... 405
14.5 Equity Appendix: Stakeholder Feedback ... 413
14.6 Workforce Appendix: Key Contextual Factors Regarding the Model ... 415
References ... 417

List of Figures

Figure EX-1. The BAU scenario shows some reduction in carbon-dioxide (CO2) emissions from transportation as the state's current zero-emission vehicle and low-carbon fuels policies play out. 3

Figure EX-2. CO_2 emissions and fuel consumption projections in the LC1 scenario. 4

Figure EX-3. Difference in costs (expenditures) for vehicles between the LC1 and BAU scenarios (LC1 minus BAU) over time.5

Figure EX-4. Annual Light-Duty Vehicle Sales, projected out to 2050 according to the BAU scenario and LC1 scenario. 8

Figure EX-5. Zero-emission freight vehicle sales projected out to 2050 in the BAU scenario and the LC1 scenario. 10

Figure EX-6. Change in VMT as compared to 2015, projected to 2050 according to the BAU scenario and the LC1 scenario 12

Figure EX-7. Carbon intensity of transportation fuels projected to 2050 according to the BAU and LC1 scenarios 14

Figure 2.1. Impact of COVID-19 on GHG emission. From https://www.nature.com/articles/s41558-020-0797-x 33

Figure 2.2. History of crude oil prices (future contracts). 34

Figure 2.3. California Highway Travel (Source Caltrans 2020) 35

Figure 3.1. Greenhouse gas emissions by source (CARB 2018) 37

Figure 3.2. California Transportation Emissions over Time (CARB) 38

Figure 3.3. History of Emissions by Transportation Segment. 39

Figure 3.4. State Transportation Funding Flow. 40

Figure 3.5. California LDV Fleet Composition (2018) by Fuel Type 44

Figure 3.6. Share of BEVs and PHEVs in New Vehicle Registration (Source: California New Car Dealers Association)........ 45

Figure 3.7. EVs as share of all vehicles 46

Figure 3.8. CVRP Applications by Fuel Type (2010-2019) 47

Figure 3.9. CVRP Applications by Vehicle Make (BEVs) 48

Figure 3.10. CVRP Applications by Vehicle Make (PHEVs) 48

Figure 3.11. Used PEV transactions in California 49

Figure 3.12. Spatial and Lorenz Distribution of Used and New PEVs in California 50

Figure 3.13. Charging options at Home and Electric Vehicle Supply Equipment (EVSE) Types 52

Figure 3.14. Charging Behavior of BEV and PHEV Users Who Responded to the Initial Survey (N=7,979) 53

Figure 3.15. Fast charging distance from Home 54

Figure 3.16. Fast charging frequency by distance from home 55

Figure 3.17. Fuel Cell Vehicle Sales by Model, Country, and Model for California 56

Figure 3.18. California Active Hydrogen Station Map. Source: https://cafcp.org/stationmap 57

Figure 3.19. Number of California trucks in selected categories 59

Figure 3.20. Number of Alternative Fuel Trucks in California 60
Figure 3.21. Average Annual Vehicle Miles Traveled per Vehicle by Major Vehicle Category 60
Figure 3.22. Daily VMT in California - ARB Baseline Projections 61
Figure 3.23. Per-Capita VMT Trends for U.S., California, and Example States - Eno Transp. Found. (2019) [65] 68
Figure 3.24. Modeled Daily VMT for Light-Duty Cars in California by County from CSTDM 69
Figure 3.25. Trends in U.S. VMT by Mode 70
Figure 3.26. Passenger-Miles Traveled by Mode in National and California Datasets 71
Figure 3.27. VMT per capita compared to GDP per capita from 1936 to 2016. 72
Figure 3.28. Estimated TNC VMT Percentage for Six U.S. Regions. 79
Figure 3.29. Daily VMT for Light Duty Trucks in California by county 87
Figure 3.30. Daily VMT for Medium Duty Trucks in California by county 88
Figure 3.31. Daily VMT for Heavy Duty Trucks in California by county 89
Figure 3.32. Caltrans Smart Mobility Tool 91
Figure 3.33. Transportation Fuel Consumption in California. 92
Figure 3.34. Total LCFS credit value 2016 through First Quarter of 2020. 93
Figure 3.35. The gasoline pool has remained relatively stable year over year. 94
Figure 3.36. Diesel and Diesel Substitute Consumption in California. 97
Figure 3.37. Fuel Volumes and LCFS Credit Generation by fuel. 98
Figure 3.38. Expected compliance with the LCFS by fuel 99
Figure 3.39. Expected compliance with the LCFS by fuel 100
Figure 3.40. Evolution of total annual PM emissions from transportation in California 109
Figure 3.41. Evolution of total annual NOx emissions from transportation in California 110
Figure 3.42. Evolution of total annual SOx emissions from transportation in California 110
Figure 3.43. Evolution of total annual CO2 emissions from transportation in California 111
Figure 3.44. 2019 Employment Estimates by Supply Chain in California’s Transportation Sector 113
Figure 3.45. 2019 Employment Estimates for the Transportation Services Supply Chain by Subdivision 125
Figure 4.1. Basic modeling flow in the Transportation Transitions Model (TTM). 131
Figure 4.2. Vehicle miles traveled in the BAU scenario. 133
Figure 4.3. Sales shares of zero-emission LDVs, trucks, and buses in the BAU 134
Figure 4.4. Fuel consumption by fuel type in the BAU scenario. 134
Figure 4.5. Life cycle GHG emissions from Fuels – BAU. 135

Figure 4.6. Comparison of this study’s BAU (bars furthest left) to other prominent BAU studies of the transportation sector for LDV stocks. 136

Figure 4.7. ZEV Sales Shares in the LC1 Scenario 137

Figure 4.8. Light-duty vehicle (LDV) ZEV sales shares by technology in the LC1 scenario. 138

Figure 4.9. Sales shares of LDVs in the LC1 scenario for 2030 and 2045 139

Figure 4.10 Stock shares in the LC1 scenario for the vehicle fleet in 2030 and 2045. 140

Figure 4.11. Fuel consumption by fuel type in the LC1 scenario for all fuels and non-petroleum fuels. 142

Figure 4.12. GHG emissions in the LC1 scenario. 143

Figure 4.13. Differences between the LC1 and BAU scenarios (i.e., LC1 minus BAU) in expenditures on vehicles and fuels. 144

Figure 4.14. Expenditure differences between the LC1 and BAU scenarios (LC1 minus BAU) separated for LDVs (*top*) and trucks/buses (*bottom*) 145

Figure 4.15. Life-Cycle GHG emissions each year from Fuels, in the LC1 and BAU scenarios 146

Figure 4.16. Total gasoline and gasoline substitutes each year in the LC1 scenario 148

Figure 4.17. Comparison of a linear decline in gasoline consumption to the modeled trajectory in LC1. 149

Figure 4.18. Total diesel and diesel substitutes in the LC1 scenario out to 2050 150

Figure 4.19. LCFS credit generation by fuel category in the LC1 scenario 151

Figure 4.20. LCFS credit balance in the LC1 scenario 152

Figure 4.21. Cellulosic and residual oil biofuel costs, average and range from techno-economic analysis literature 153

Figure 4.22. LDV (*top*) and HDV (*bottom*) sales shares by side case 157

Figure 4.23. Sales shares in 2045 by technology and market class for the High Fuel Cell side case (*top*) and LC1 scenario (*bottom*). 158

Figure 4.24. BEV/PHEV and FCEV sales by side case through 2045. 159

Figure 4.25. Fuel consumption by fuel type by year. 161

Figure 4.26. CO_2 emissions by fuel and scenario in 2030 and 2045 162

Figure 4.27. Cost differences between the LC1 and side case scenarios vs. (minus) the BAU scenario, in different time periods 163

Figure 4.28. Expenditure Difference, LC1-BAU, for baseline, low, and high oil costs in the LC1 scenario. 165

Figure 5.1. Tailpipe emissions from E3’s Pathways model as used in the 2017 Scoping Plan. 166

Figure 6.1. Who purchase new light-duty vehicles (LDVs) 172

Figure 6.2. Consumer consideration of BEVs and PHEVs is unchanging. 173

Figure 6.3. Adoption of first vehicle by household group and fleet size. (LD, light-duty) 176

Figure 6.4. Adoption of first ZEV by household type 177

Figure 6.5. Adoption of first ZEV by number of household vehicles 177

Figure 6.6. Allocation of new vehicles by what they replace 178

Figure 6.7. Total ZEV ownership by household category 179

Figure 6.8. Electrification progress by first, second, etc. vehicle in the household 179

Figure 6.9. Charger stock 182

Figure 6.10. Demand for new chargers through 2045 183

Figure 6.11. Proportion of charging by location – home, work, or public level 2 183

Figure 6.12. Proportion of households by PEV ownership and housing type 187

Figure 6.13. Type of ZEV allotted for TCO comparison 188

Figure 6.14. Average capital cost difference between a ZEV and an ICEV-fleet 189

Figure 6.15. Proportion of household with capital cost benefits from purchasing ZEVs 190

Figure 6.16. Average operating cost difference between a ZEV and an ICEV fleet 191

Figure 6.17. Average TCO difference between a ZEV and an ICEV-fleet 192

Figure 6.18. Proportion of household with capital cost benefits from purchasing ZEVs 193

Figure 7.1. Daily Freight Truck Trips by CSF2TDM Truck Class for 2020 203

Figure 7.2. 2020 Average Trip Length by CSF2TDM Truck Class 204

Figure 7.3. 2020 Trip Length Distribution by CSTDM Commodity Groups and Truck Class 204

Figure 7.4. 2020 Trip Length Distribution by CSTDM Commodity Groups for Class 8 Trucks 205

Figure 7.5. Long-haul truck fleet projections for BAU (*left*) and LC1 (*right*). 212

Figure 7.6. Zero-Emissions Sales Schedule by Vehicle Category under California's Advanced Clean Trucks regulation. 214

Figure 7.7. BAU Medium- and Heavy-Duty Vehicle Hydrogen Refueling Stations year 2020–2050 (500 and 1,000 kg Station Capacities): Class 4–8 223

Figure 7.8. LC1 Medium- and Heavy-Duty Vehicle Hydrogen Refueling Stations for Class 2–b–3 224

Figure 7.9. C1 Medium- and Heavy-Duty Vehicle Hydrogen Refueling Stations for Class 4–8. 225

Figure 7.10. BAU Medium- and Heavy-Duty Vehicle Chargers for Different Charger-to-Vehicle Ratios 226

Figure 7.11. LC1 Medium- and Heavy-Duty Vehicle Chargers for Different Charger-to-Vehicle Ratios 227

Figure 7.12. Distribution of Level 2 and DC Fast Charging for BAU Trajectory with different charger:vehicle ratios. 228

Figure 7.13. Distribution of Level 2 and DC Fast Charging for LC1 Trajectory 229

Figure 8.1. Factors Influencing Vehicle Miles of Travel (Source: Polzin, et al. 2004 [278]) 232

Figure 8.2. Shares by Category of VMT Strategy Per-Capita Reductions 237

Figure 9.1. Lifecycle GHG emissions from fuels each year in scenarios analysis 257

Figure 9.2. Diesel Pool transition in the BAU and LC1 scenarios to 2050 258

Figure 9.3. Gasoline pool transition in the BAU and LC1 scenarios 259

Figure 9.4. LCFS credit generation in the BAU and LC1 scenarios 260

Figure 9.5. LCFS credits, Deficits, banked credit balance, and LCFS target in the BAU and LC1 scenarios 262

Figure 9.6. CCS required to fully mitigate emissions, by carbon intensity of fuel 268

Figure 9.7. Technological readiness assessments for biofuel conversion technologies. 272

Figure 10.1. 2025 BAU and LC1 Difference in PM2.5 Concentrations 288

Figure 10.2. 2030 BAU and LC1 Difference in $PM_{2.5}$ Concentrations 289

Figure 10.3. 2035 BAU and LC1 Difference in PM2.5 Concentrations 290

Figure 10.4. 2040 BAU and LC1 Difference in $PM_{2.5}$ Concentrations 291

Figure 10.5. 2045 BAU and LC1 Difference in $PM_{2.5}$ Concentrations 292

Figure 10.6. Comparison of changes in $PM_{2.5}$ concentrations in 2045 (BAU vs LC1). 293

Figure 10.7. Overview of the CMAQ modeling methods utilized for the air quality assessment 294

Figure 10.8. Emission reductions from on-road vehicles in the LC1 trajectory relative to the BAU trajectory. 296

Figure 10.9. Difference in NO_x emissions in LC1 versus BAU. 296

Figure 10.10. Difference predicted for the LC1 trajectory for annual average NO_x concentrations 298

Figure 10.11. Difference predicted for the LC1 trajectory for (a) annual average ozone and (b) average MD8H ozone from April-October 298

Figure 10.12. Difference predicted for the LC1 trajectory for annual average PM2.5 299

Figure 10.13. Annual average difference in NO_x concentrations (LC1 - BAU) 300

Figure 10.14. Annual average difference in $PM_{2.5}$ concentrations (LC1 vs. BAU) 301

Figure 10.15. Annual average difference in MD8H ozone concentrations (LC1 vs. BAU) 301

Figure 10.16. Annual average difference in NO_x concentrations (LC1 vs. BAU) with DAC outlined 302

Figure 10.17. Annual average difference in NO_x concentrations (LC1 vs. BAU) with DAC outlined 303

Figure 10.18. Annual average difference in MD8H ozone concentrations (LC1 vs. BAU) with DAC outlined 303

Figure 10.19. Statewide annual incidence and valuation health benefits 307

Figure 10.20. Annual incidence and valuation health benefits of major air basins 308

Figure 10.21. Valuation health benefits of major air basins in 2045 using CMAQ 310

Figure 11.1. California Climate Investments for Disadvantaged and Low-Income Communities 311

Figure 11.2. CalEnviro Screen tool 313

Figure 11.3. SB 535 Disadvantaged Communities and AB 1550 Low-Income Communities 314

Figure 11.4. Breakdown of the Social Determinants of Health. 318

Figure 11.5. Disadvantaged communities in the Los Angeles Port Area 321

Figure 11.6. Disadvantaged communities in the Stockton Area 322

Figure 12.1. Projected estimates for annual total FTEs resulting from expansion of ZEV-related industries in California in thousands of FTEs by sector, 2020-2045. 328

Figure 12.2. Projected estimates for annual total FTEs supported by ICEV-related industries (*top*) and (*bottom)* cumulative year-over-year FTE reductions resulting from contractions in these industries in California in thousands of FTEs by sector, 2020-2045 329

Figure 12.3. Projected estimates for annual direct, indirect, and induced jobs resulting from (*top*) new ICEV sales, (*middle*) fossil fuel consumption, and (*bottom*) ICEV maintenance in California in thousands of FTEs, 2020-2045. 332

Figure 12.4. Projected estimates for annual direct, indirect, and induced jobs resulting from (*top*) new BEV sales, (*middle*) consumption of electricity for transportation, and (*bottom*) BEV maintenance in California in thousands of FTEs, 2020-2045. 343

Figure 12.5. Projected estimates for annual direct, indirect, and induced jobs resulting from (*top*) new FCEV sales, (*middle*) hydrogen fuel consumption, and (*bottom*) FCEV maintenance, in California in thousands of FTEs, 2021-2045. 349

Figure 12.6 Projected estimates for annual direct, indirect, and induced jobs resulting from EV charging infrastructure construction and other EVSE installation in thousands of FTEs, 2021-2045. 351

Figure 12.7 Projected estimates for annual direct, indirect, and induced job creation from hydrogen refueling infrastructure construction in thousands of FTEs, 2021-2045. 353

Figure 14.1. HHDT diesel emission factors for CA’s 68 county–air basin sub areas 405

Figure 14.2. HHDT gasoline emission factors for CA’s 68 county–air basin sub areas 406

Figure 14.3. HHDT NG emission factors for County – Air Basin sub areas (36 observations) 407

Figure 14.4. Passenger electric vehicle PM2.5 emission factors (68 observations) 408

Figure 14.5. Passenger electric vehicle ROG emission factors for (68 observations) 409

Figure 14.6. Light-duty Gas NH3 emission factors for County – Air Basin sub areas (68 observations) 410

Figure 14.7. Heavy-duty Gas NH3 emission factors for 68 County - Air Basin sub areas 411

Figure 14.8. Heavy-duty diesel NH3 emission factors for 68 County–Air Basin sub areas 412

List of Tables

Table EX-1. Benchmarks for each transportation metric according to 2045 net zero goal 16

Table EX-2. Battery, vehicle, and charging benchmarks 17

Table 1.1. Monetary and non-monetary external costs of motor-vehicle use. 31

Table 3.1. Total vehicle population by drivetrain type (2018) 44

Table 3.2. Number of chargers California 2020 53

Table 3.3. FHWA weight classes (Source AFDC [54]) 58

Table 3.4. Examples of Heavy-Duty Zero-Emission Vehicles and Technical Specifications 63

Table 3.5. Summary of HDV incentive programs 65

Table 3.6. VMT by Functional Road Category in California - 2018 (millions) 67

Table 3.7. Summary of Roundtrip Carsharing Impact Studies 73

Table 3.8. Summary of One-way and Person-to-Person (P2P) Carsharing Impact Studies 74

Table 3.9. Summary of Docked Bikesharing Impact Studies 75

Table 3.10. Summary of Dockless Bikesharing Impact Studies 77

Table 3.11. Summary of Studies on VMT from TNC Vehicles 78

Table 3.12. Operational Statistics for California Transit Agencies – 2015 / 2018 82

Table 3.13. Fuels Types and Amounts Used by California Transit Agencies – 2015 / 2018 83

Table 3.14. Pricing Policy Effect Estimates by Category [126] 84

Table 3.15. Consideration status and estimated employment for industries in California's fossil fuel supply chain across Carbon Neutrality Studies 1 & 2 114

Table 3.16. 2019 Employment Estimates for California’s Fossil Fuel Supply Chain 118

Table 3.17. 2019 Employment Estimates for California’s Electricity Supply Chain 119

Table 3.18. 2019 Employment Estimates for California’s General Vehicle Supply Chain 122

Table 3.19. 2019 Employment Estimates for California’s Motor Vehicle Supply Chain 123

Table 3.20. 2019 Employment Estimates for California’s Electric Vehicle Supply Chain 123

Table 3.21. 2019 Employment Estimates for California’s Transportation Services Supply Chain 126

Table 4.1. Existing Policies to target reduction of GHG emissions in the transportation sector 132

Table 4.2. LCFS targets trajectory from 2027 to 2045 147

Table 4.3. LC1 and side cases for road vehicles 156

Table 4.4. Sensitivity Case Input Values. 164

Table 4.5. Sensitivity Case Costs 164

Table 5.1 Key milestones 168

Table 6.1. Total households and vehicles in the four groups used for fleet electrification modeling 174

Table 6.2. ZEV allotment rule for TCO comparison 186

Table 6.3. Milestones Barriers and policies for 100% LDV electrification 198

Table 7.1. Drayage Truck Emissions 208

Table 7.2. Summary of California’s Drayage Truck Regulation 209

Table 7.3. 2020 Air pollutant emissions for Class 2b and 3 vehicles in California (ton/year) 216

Table 7.4. 2020 Off-road construction and mining equipment emissions 219

Table 7.5. 2020 On-road construction trucks emissions 219

Table 8.1. VMT by Place Type “Importance” Weighting by Analysis Year 235

Table 8.2. Analysis Results - Per-Capita VMT Reductions Over Time (5-Year Changes) by Strategy 236

Table 8.3. Qualitative Summary of VMT Related Policy Interaction Effects 250

Table 9.1. Total On-Road Electricity Consumption in million gge, 2025 and 2030, in this study and other comparable models. 265

Table 9.2. Petroleum and alternative fuel volumes in the LC1 scenario. 269

Table 10.1. Abbreviations 282

Table 10.2. Vehicle Classes Mapping 285

Table 10.3. Emissions comparison 286

Table 10.4. Concentration Response Functions Selected for the Health Analysis 304

Table 10.5. Estimated 2045 LC1 Health Benefits via InMAP+BenMAP 306

Table 10.6. Estimated 2045 LC1 Health Benefits via CMAQ+BenMAP 309

Table 10.7. Estimated 2045 LC1 Health Benefits within the selected DAC Communities 310

Table 12.1. Estimated direct and indirect annual FTEs in 2020 and 2045 and the calculated reduction for the top 5 occupations in each ICEV-related sector in California. 333

Table 12.2. Declines in estimated annual FTEs in the top five affected industries in ICEV-related sectors between 2020 and 2045. 335

Table 12.3. Estimated Employment and Wages for Declining Industries in California’s Fuel and Vehicle Supply Chains 337

Table 12.4. Demographic Profile of Declining Industries 339

Table 12.5. Top 5 occupations by total FTE job-years resulting from expenditures on new BEV sales, electricity consumption for transportation, and BEV maintenance, respectively, in California, 2020-2045. 344

Table 12.6. Estimated Employment and Wages for Expanding Industries in California’s Fuel Supply Chain 345

Table 12.7. Demographic Profile of Growing Industries 346

Table 12.8. Top 5 occupations by total FTE job-years resulting from expenditures on new FCEV sales, hydrogen fuel consumption, and FCEV maintenance, respectively, in California, 2021-2045. 350

Table 12.9. Top 5 occupations related to EV charging infrastructure construction and other EVSE installation by FTE job-years, 2021-2045. 352

Table 12.10. Top 5 occupations by FTE job-years created from expenditures on new hydrogen refueling station construction in California, 2021-2045. 353

Table 14.1. Probability of Charger Installation for Single-family Homes 360

Table 14.2. Purchase cost of Plug-in Electric Vehicles (Teardown Approach) 361

Table 14.3. Purchase cost of ICEVs 361

Table 14.4. Fuel price assumptions 362

Table 14.5. Vehicle Efficiency assumptions 362

Table 14.6. Total cost of ownership calculation 363

Table 14.7. Estimated Effects on VMT of Built Environment Elements Based on Empirical Literature 364

Table 14.8. Policy Assumptions and Population Growth Rate Adjustments by Place Type 367

Table 14.9. Density thresholds for place types if density is increasing 368

Table 14.10. Density thresholds for place types if density is decreasing 368

Table 14.11. Elasticity Values from Fuel Tax Policy/Strategy 370

Table 14.12. Assumed Gasoline Vehicle Market Shares Over Time 370

Table 14.13. Analysis Variables for Fuel Tax Policy Analysis 371

Table 14.14. Elasticity Estimates for Road Usage Fees 372

Table 14.15. Elasticity Estimates for Road Usage Fees 372

Table 14.16. TNC Market Shares by Place Type and Year 373

Table 14.17. TNC Pooling Ratios by Place Type 374

Table 14.18. Resulting TNC Pooling Ratios with Policy Change 374

Table 14.19. Percentage Decreases in VMT From Pooled Ride Services by Place Type 374

Table 14.20. Factors Needed for Employee Parking Elasticities 376

Table 14.21. Percentage of Employed Population in Each Place Type (USCB, 2018) 376

Table 14.22. VMT Reduction V.S. Baseline (Employee Parking) 377

Table 14.23. Per-Capita VMT Reductions Over Time (5-Year Changes) by Employee Parking Pricing 377

Table 14.24. Factors Needed for All Parking Elasticities 378

Table 14.25. VMT Reduction V.S. Baseline (All Parking) 379

Table 14.26. Per-Capita VMT Reductions Over Time (5-Year Changes) by Parking Pricing Applied to General Population 379

Table 14.27. Factors Needed for Carpooling Elasticities 380

Table 14.28. VMT Reduction V.S. Baseline (Carpooling) 381

Table 14.29. Per-Capita VMT Reductions Over Time (5-Year Changes) by Carpooling 381
Table 14.30. Factors Needed for Telework Elasticities 382
Table 14.31. Plan Bay Area Policy V.S. Assumptions Lookup Table 383
Table 14.32. Percentage of Teleworkers by Place Type 383
Table 14.33. SOV Mode Share (USCB, 2018) 384
Table 14.34. Per-Capita VMT Reductions Over Time (5-Year Changes) by Telework 384
Table 14.35. Factors Needed for Shared Micromobility Elasticities 385
Table 14.36. Place Type Specific Shared Micromobility Factors (NABSA, 2020) 385
Table 14.37. City Sizes vs. Place Types Lookup Table 385
Table 14.38. Per-Capita VMT Reductions Over Time (5-Year Changes) by Shared Micromobility 386
Table 14.39. Carbon Intensity improvement rates for various fuels, under the BAU and LC1 scenarios 391
Table 14.40. Other parameters controlled from the Control Panel 391
Table 14.41. Model Default Carbon Intensities (g/MJ). 399
Table 14.42. Carbon Intensities (g/MG) common to all scenarios, 2031-2045 399
Table 14.43. Stakeholder feedback from workshop held on equity after Study 1 was released. 413

Glossary

AB	Assembly Bill
ACT	Advanced Clean Truck
AFV	alternative fuel vehicle
AHSC	Affordable Housing and Sustainable Communities
APTA	American Public Transportation Association
AQIP	Air Quality Improvement Program
AQMD	Air Quality Management District
ATP	Active Transportation Program
AV	automated vehicles
BART	Bay Area Rapid Transit
BAU	business as usual
BBD	bio-based diesel
BBG	bio-based gasoline
BD	biodiesel
BenMAP	Environmental Benefits Mapping and Analysis Program
BEV	battery electric vehicle
BLS	United States Bureau of Labor Statistics
CaFCP	California Fuel Cell Partnership
CAFE	Corporate Average Fuel Economy
CalSTA	California State Transportation Agency
CARB	California Air Resources Board
CAV	clean air vehicle
CCS	carbon capture and sequestration
CCSF	California's Clean Fuel Future
CEC	California Energy Commission
CEPAM	California Emissions Projection Analysis Model
CHTS	California Household Travel Survey
CI	carbon intensity
CMAQ	Community Multiscale Air Quality Modeling System
CNG	compressed natural gas

CO	carbon monoxide
CO2	carbon dioxide
CPUC	California Public Utilities Commission
CSF2TDM	California Statewide Freight Forecasting and Travel Demand Model
CSTDM	California Statewide Travel Demand Model
CTP	Clean Trucks Program
CVA	Clean Vehicle Assistance
CVRP	Clean Vehicle Rebate Program
DACs	disadvantaged communities
DGE	diesel gallon-equivalent
DMV	Department of Motor Vehicles
DOE	US Department of Energy
DOT	US Department of Transportation
E10	10% ethanol
EIA	Energy Information Administration
EJ	environmental justice
EMFAC	EMission FACtor
EPA	Environmental Protection Agency
EV	electric vehicle
EVSE	electric vehicle supply equipment
FCEV	fuel cell electric vehicle
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
FTE	full-time equivalent
GDP	gross domestic product
GGE	gasoline gallon-equivalent
GHG	greenhouse gas
GPY	gallon per year
GVWR	gross vehicle weight rating
HDV	heavy-duty vehicle
HEV	hybrid-electric vehicle

HFC	high fuel cell (scenario)
HLF	high liquid fuel
HOT	high-occupancy toll
HOV	high-occupancy vehicle
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program
HZ	high zero emission vehicle (scenario)
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
InMAP	Intervention Model for Air Pollution
ICSC	Illustrative Compliance Scenario Generator
LC1	central low-carbon scenario
LCFS	Low Carbon Fuel Standard
LD	light-duty
LDV	light-duty vehicle
LiDAR	Light Distance and Ranging
LNG	liquefied natural gas
LOS	level of service
MDV	medium-duty vehicle
$\mu g/m^3$	micrograms per cubic meter
M/HD	medium- and heavy-duty
MJ	megajoule
MMT	million metric tonnes
MPO	Metropolitan Planning Organization
MSRC	Mobile Source Air Pollution Reduction Review Committee
MV	motor vehicle
NAAQs	National Ambient Air Quality Standards
NG	natural gas
NH3	ammonia
NHTS	National Household Travel Survey
NOx	nitrogen oxides
OEHHA	Office of Environmental Health Hazard Assessment

OPR	Governor’s Office of Planning and Research
P2P	person-to-person
PDTR	Ports of Los Angeles and Long Beach drayage trucks registry
PEV	plug-in electric vehicle
PFCEV	plug-in fuel cell electric vehicle
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
PMT	person miles traveled
ppb	parts per billion
PTO	power takeoff
RD	renewable diesel
RFS	Renewable Fuel Standard
RNG	renewable natural gas
ROG	reactive organic gas
SAF	sustainable aviation fuel
SAFE	Safer Affordable Fuel Efficiency
SAV	shared automated vehicle
SB	Senate Bill
SCS	Sustainable Communities Strategy
SIP	State Implementation Plan
SMOKE	Sparse Matrix Operator Kernel Emissions tool
SO2	sulfur dioxide
SOx	sulfur oxides
SPBP	San Pedro Bay Ports
SUV	sport utility vehicles
TCO	total cost of ownership
TNC	transportation network company
TTM	Transportation Transitions Model
V2G	vehicle-to-grid
VMT	vehicle miles traveled
VOC	volatile organic compound

VOMS	vehicles operated in maximum service
VSL	value of statistical life
ZE	zero-emission
ZEB	zero-emission bus
ZEV	zero-emission vehicle

Executive Summary

Executive Summary

Study Goal

California has taken a leadership role in reducing carbon emissions, setting a goal of carbon neutrality by 2045. Decarbonizing transportation, the largest source of emissions in the state, will be key to achieving that goal. The state is also committed to addressing air pollution, improving equity, and better supporting the economy—all of which interact with transportation. The purpose of this study is to provide a research-driven analysis of possible policy options that could, if combined, put the state on the pathway to a carbon-neutral transportation system by 2045. While there are several credible studies of a path to 80% reductions in emissions by 2045, this is the first report to comprehensively evaluate a path to carbon neutrality within this time frame. This study also seeks to center important factors such as equity, health, and workforce impacts in the analysis because a transition to zero-carbon transportation also needs to advance these goals.

Funding for the research was provided by the Budget Act of 2019 through a contract with the California Environmental Protection Agency. The research for this study was performed by a team of researchers from the four University of California Institutes of Transportation Studies (UC ITS), established by the California Legislature in 1947. The UC ITS is a network with branches at UC Berkeley, UC Davis, UC Irvine, and UCLA. These campuses have decades of experience on all the relevant topics for the study. The UC Davis Policy Institute for Energy, Environment, and the Economy coordinated the project management and policy analysis for the study, and the UC Davis Center for Regional Change led the equity and environmental justice research and coordinated engagement with stakeholders.

Priorities and Structure

Reducing emissions is not a goal that can be pursued independently of the many other priorities for the state and its residents. Transportation has historically contributed to pollution, equity problems, and environmental degradation. Transportation is also an important employer and essential for the economy by supporting goods movement and access to job opportunities. To account for these important considerations, the study was performed with attention to improving outcomes in all the following areas:

- Equity and Justice
- Health
- Environment
- Resilience and Adaptation
- High Quality Jobs
- Affordability and Access
- Minimize Impacts Beyond Our Borders

Transportation relies on a complex system of systems. To manage this complexity, this study is based on an overall scenario analysis and divides the policy analysis into four transportation system subsectors. The results from analysis in each area are incorporated into a single integrating analysis of an overall low carbon scenario and four side cases. These cases are compared to a “business as usual” scenario. The scenario analysis tool used in this study is the UC Davis Transportation Transitions Model (TTM), documented in the Scenarios chapter.

The policy analysis was conducted in four subsectors. These are:

- Light-duty vehicles: cars and light trucks, mostly used for personal transportation. These vehicles are responsible for 70% of transportation emissions.
- Heavy-duty vehicles: medium- and heavy-duty vehicles, mostly used for goods movement and commercial and industrial use, as well as off-road equipment.
- Vehicle miles traveled: the demand for travel and mode selection that defines total vehicle use.
- Fuels: liquid petroleum fuels that dominate transportation today and renewable and alternative fuels that can act as substitutes.

To account for several critical implications of policy choices, the analysis also goes in depth into three priority topics. These are:

- Health: Pollutants from transportation, especially particulate matter and nitrogen oxides, are a significant contributor to negative health outcomes. Active transportation modes such as walking and biking are associated with better health. Shifting to a cleaner and more active transportation system would have significant health benefits, especially in burdened communities.
- Equity and environmental justice: Transportation has a significant historical role in creating and exacerbating inequities. Depending on their implementation, the clean transportation policies discussed in this report have the potential to reverse this.
- Workforce and jobs impacts: Transportation is a major employer and supports the economy. A clean transportation system could have significant effects on the workforce, both creating and disrupting whole sectors.

Scenarios

California has already developed and implemented a suite of policies that are steering the state towards lower emissions transportation. As a first step for the analysis, the research team developed a business-as-usual (BAU) scenario, which reflects the expected impact of the policies currently implemented. This, like other scenarios, is not a forecast but rather a reference point to compare lower carbon scenarios. The purpose of the BAU scenario is to serve as a plausible outcome with the current policy environment and as a point of reference for other scenarios. Figure EX-1 shows the projected greenhouse gas (GHG) emissions from transportation within the BAU scenario.

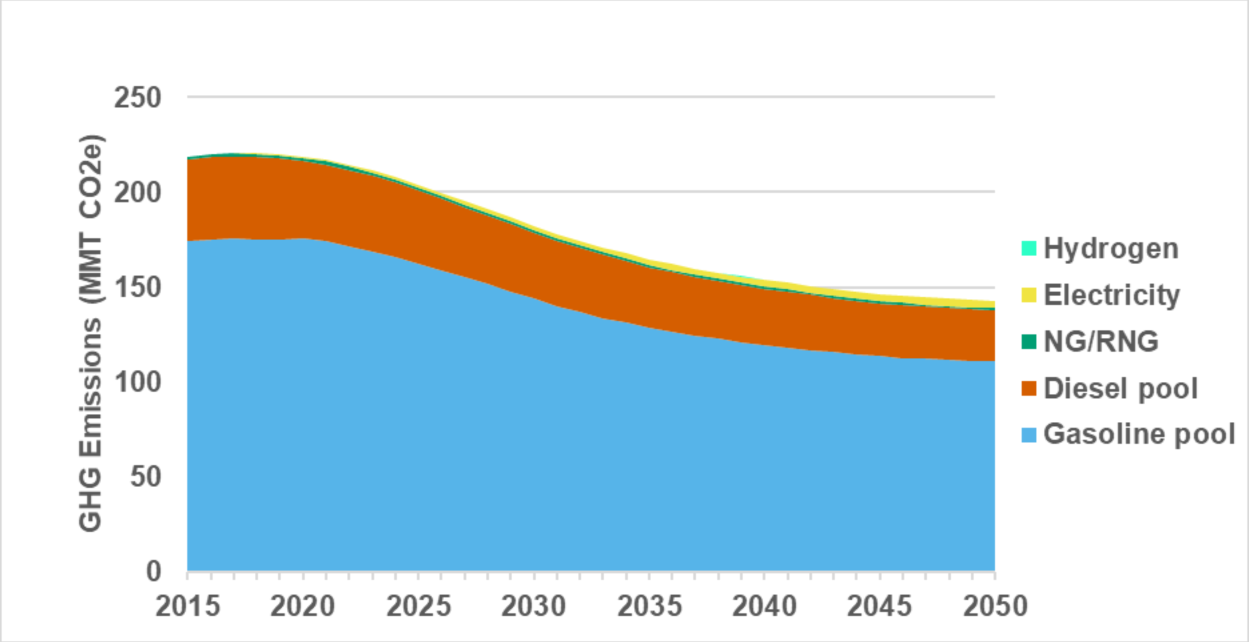
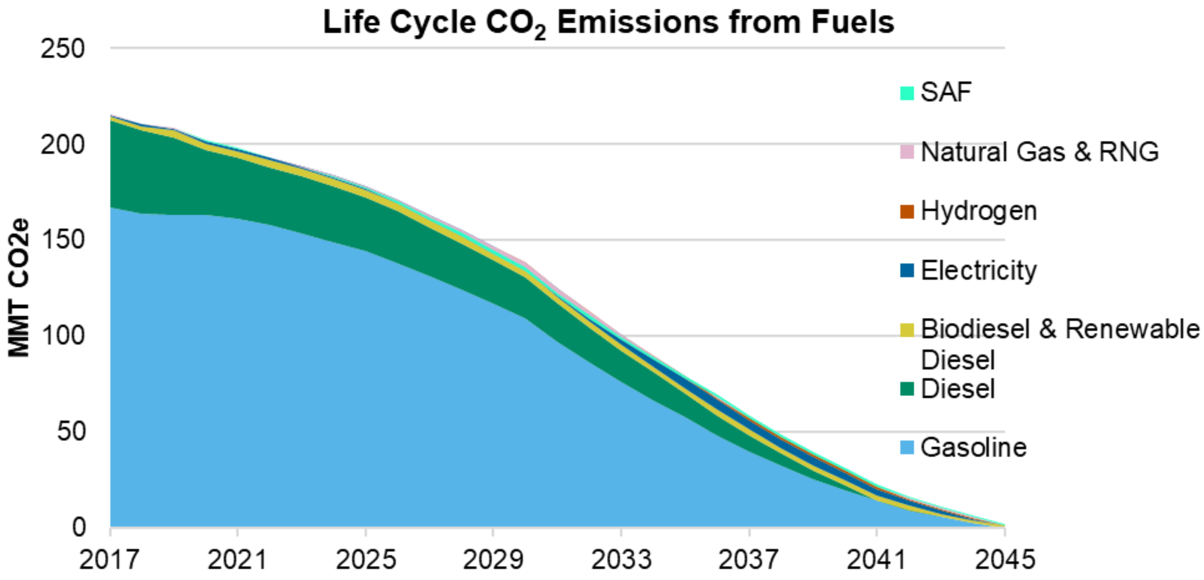


Figure EX-1. The BAU scenario shows some reduction in carbon-dioxide (CO2) emissions from transportation as the state's current zero-emission vehicle and low-carbon fuels policies play out. However, the BAU drop in emissions is less than one-third of the way to carbon-neutral by 2045. (GHG, greenhouse gas; MMT, million metric tonnes)

The main research efforts in this study are oriented towards exploring policy options that could put the state on a pathway to a carbon-neutral transportation system by 2045. The core results from the study in terms of emissions impacts are incorporated in a central Low Carbon (LC1) scenario. This scenario includes GHG emissions, vehicle sales, fuel consumption, carbon intensity, and changes in VMT. The LC1 scenario is referred to as 'central' to distinguish it from other low-carbon scenarios ('side cases') described in the full report. Figure EX-2 shows the GHG emissions and consumption of different fuel types under this scenario.



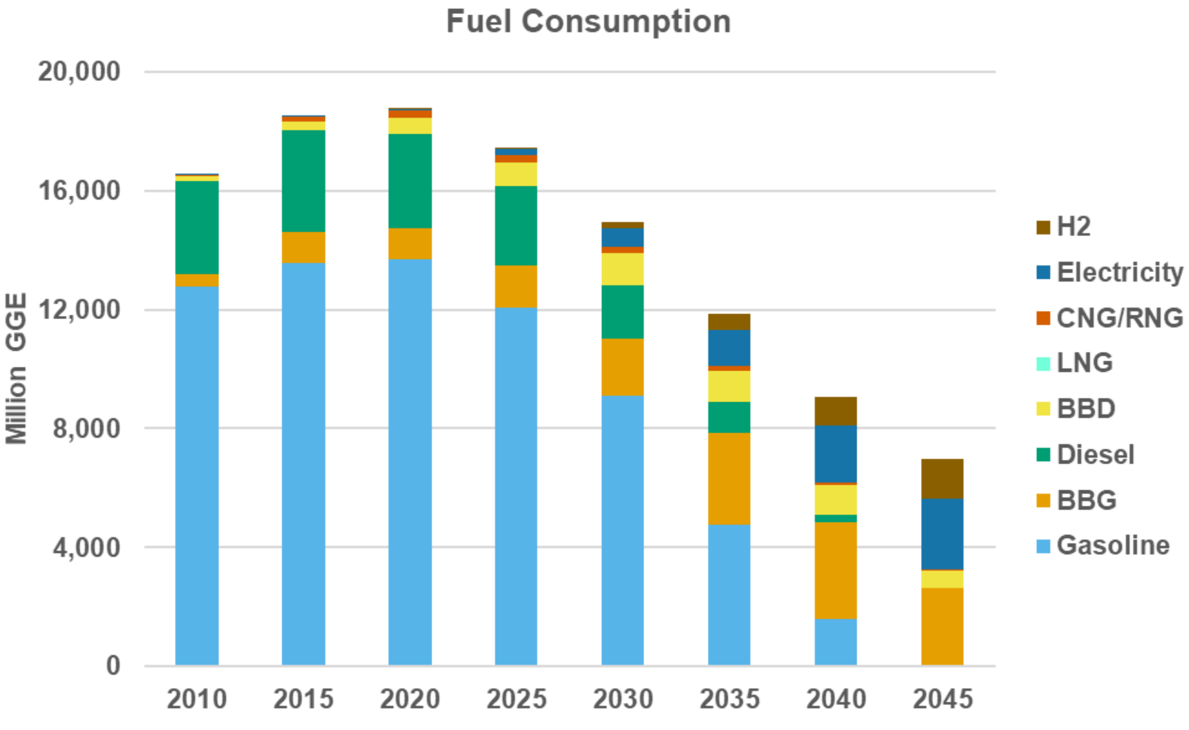


Figure EX-2. CO_2 emissions and fuel consumption projections in the LC1 scenario. The near-zero CO_2 emissions target is reached by 2045, with nearly all fossil fuels replaced by electricity, hydrogen, and biofuels at that date. (MMT, million metric tonnes; SAF, sustainable aviation fuel; H2, hydrogen; CNG/RNG, compressed natural gas/renewable natural gas; LNG, liquefied natural gas; BBD, bio-based diesel, including biodiesel and renewable diesel; BBG, bio-based gasoline, including ethanol blends and drop-in gasoline replacement fuels)

The scenario analysis includes an estimate of the total costs of the LC1 compared to the BAU scenario (Figure EX-3). The overall finding is that combined vehicle and fuel costs for the LC1 scenario are higher over the first 10 years ($10 billion cumulative from 2020 to 2030), and thereafter lower due to the reduced costs for fuel and improved vehicle technology ($177 billion savings cumulative from 2031 to 2045, for a net of $167 billion, 2020 to 2045). In 2045, the single-year total costs are approximately $23 billion lower in the LC1 scenario. These costs do not discount future cash flows to present value; however, even discounting future costs at a societal rate of 4% per year, the cumulative savings remain large, i.e., over $70 billion between 2020 and 2045. Without accounting for external costs or benefits, total undiscounted vehicle and fuel costs over the study are about $180 billion lower in the LC1 than in the BAU scenario (summed through 2045). Adding the external costs and benefits, such as the impact of reduced air pollution from cleaner vehicles and fuels, would dramatically increase the net benefits to California over the study period. The finding of net savings shows that there are significant expected economic benefits overall; this does not mean that the benefits will necessarily accrue fairly. Including equity in all policy elements can mitigate potential differential benefits and harms.

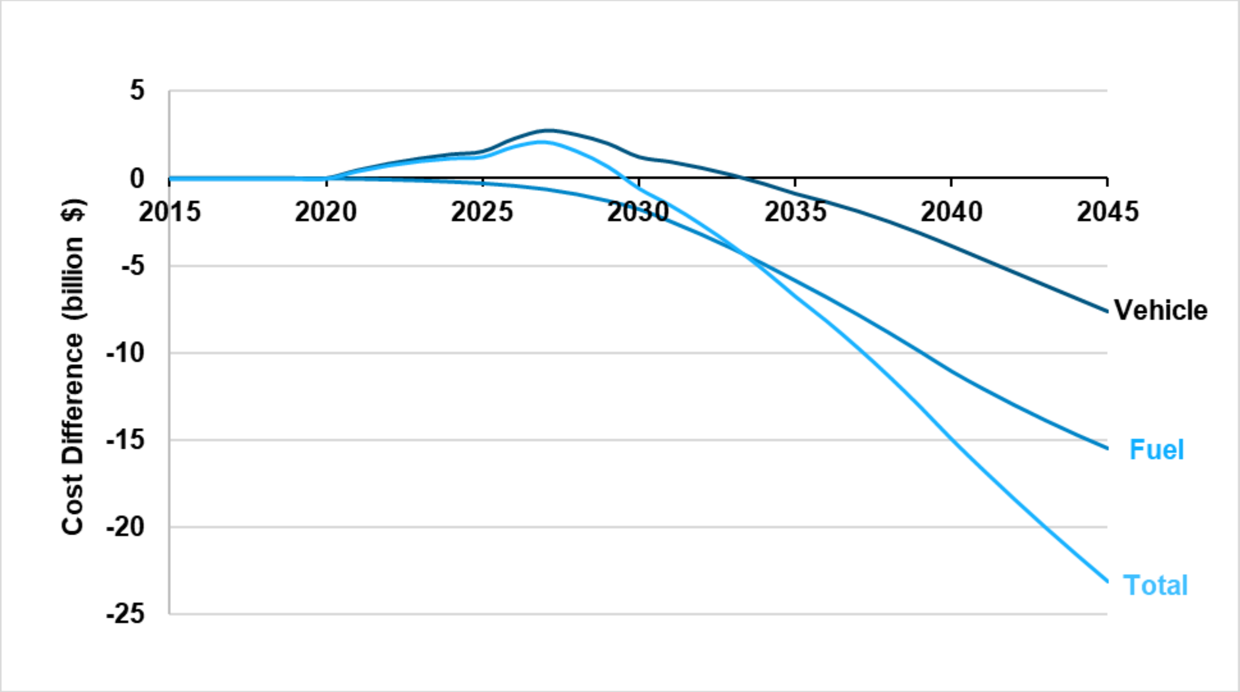


Figure EX-3. Difference in costs (expenditures) for vehicles between the LC1 and BAU scenarios (LC1 minus BAU) over time. An increase in vehicle purchase costs over the next 10 years is offset by fuel cost savings by 2030, and then deep cost reductions occur beyond that date.

Side Cases

The LC1 scenario is not intended as a forecast, in part because there is significant uncertainty in how policies and technologies could evolve to reach net zero emissions. Emissions could be reduced more or less rapidly with different combinations of stringency in the different subsectors evaluated. There are also a wide range of possible combinations of technologies within each subsector that could contribute to differing degrees of emissions reductions. To explore some elements of this uncertainty, the research team examined three side cases, each of which differs from the LC1 scenario in ways that allow more detailed analysis of certain options and tradeoffs. These side cases are documented in the Scenarios section and are:

- Accelerated light-duty and heavy-duty zero emission vehicle (ZEV) sales
- Increased use of fuel cells
- Higher use of low-carbon liquid fuels

One purpose of analyzing these side cases is to demonstrate that there are multiple possible pathways to a zero-carbon transportation system and that there is significant uncertainty in which specific path the state may follow.

Key Policies

The transition to a zero-carbon transportation system is very unlikely to happen rapidly without policy intervention. This is because many of the external costs[1] of transportation—such as congestion, pollution, and GHG emissions—are not paid for by the businesses or individuals that make key decisions, and because individuals and even many businesses do not make purchase decisions based on the total cost of ownership (TCO). This TCO issue is critical because electric vehicles (EVs) are likely to be superior on a TCO basis in less than 10 years, but buyers base their decision more on the EV purchase price, which is not optimal for the economy nor the environment. More generally, there are many rules, laws, and behaviors that persist from the past that discourage change. Announced goals and federal actions to date are not enough to move the market quickly.

Policies, regulations, and incentives are therefore needed, especially in the early stages of transition, to give direction to investments and provide cost parity and market sustainability. The main focus of this study was to explore the combination of policies that can support the transition to a zero-carbon transportation system as exemplified by the LC1 scenario. The policies examined here are analyzed in the context of their ability to, in concert, lead to a very low- or zero-carbon transportation system.

Economy Wide

This study focused on transportation-specific policies, but economy-wide policies also have played a major role. California has had economy-wide policies for reducing air pollutants since the 1960s and for reducing GHG emissions since 2006. The carbon Cap-and-Trade Program is a foundation of California's climate policy. The longest-term legislative requirement is for 40% reduction in economy-wide GHG emissions by 2030; SB 32 was adopted in 2016. In 2018 then-Governor Jerry Brown issued executive order B-55-18, which sets a target for California to be carbon neutral (carbon emitted is offset by carbon absorbed or captured) by 2045. This is the most recently adopted and most ambitious statewide goal. Achieving carbon neutrality will require significant shifts in every aspect of the state's economy, including electric generation, buildings, industry, land use and agriculture, and transportation.

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[1] External costs are those not paid by the user of a service and therefore borne by others

The Cap-and-Trade Program, administered by the California Air Resources Board (CARB) establishes an allowance budget, or cap, that declines each year to match the overall limit on statewide emissions. The Cap-and-Trade Program was called for in AB 32 in 2006 and updated through 2030 by AB 398, with some new provisions. To date, and in the near future, the cap is expected to predominantly drive change in the power sector and certain high-emitting industrial applications. Expected prices for carbon under the program are not likely to be high enough to cause significant changes in transportation, which means additional policy actions are needed (see section 5.2). Revenue from cap-and-trade allowance auctions is invested in many areas of the economy, including transportation, and is a significant source of funding for alternatives to petroleum. Significant fractions of cap-and-trade revenue are, by law, required to be invested in, or for the benefit of, disadvantaged communities (DACs). In practice, actual expenditures so far have exceeded the legislative requirements.

Other transportation-related policies have economy-wide impacts as well, notably the Low Carbon Fuel Standard (LCFS) and fuel taxes. The LCFS requires the carbon intensity of California's transportation fuel to decline over time and has supported a gradual shift from petroleum fuels to lower carbon alternatives since it came into effect in 2011. California (like all other states) taxes gasoline and diesel fuel used for transportation. Fuel taxes are generally described as a user fee mostly to pay for roads and infrastructure maintenance. As of 2018, California's fuel taxes were also indexed to inflation, which was intended to preserve their purchasing power as construction and maintenance costs increased, however, increasing vehicle fuel efficiency and the transition away from petroleum fuels will erode the aggregate revenue from this source over time.

Light-Duty Vehicles

Light-duty vehicles—cars, SUVs, minivans, and pickup trucks—are currently responsible for 70% of transportation emissions in California. Transition to a zero-carbon transportation system depends on a rapid shift to ZEVs, which could include a mix of battery-electric vehicles (BEVs), plug-in hybrid vehicles running primarily on electricity (PHEVs), and hydrogen fuel cell electric vehicles (FCEVs). These vehicles currently have higher purchase prices on average, but lower operating costs. Because the electricity grid is being decarbonized, ZEVs dramatically reduce GHG emissions and local air pollution. A key barrier to replacing gasoline and diesel vehicles with plug-in vehicles is the availability of reliable and dependable charging infrastructure at homes, workplaces, along intercity highways, and public locations in urban and suburban areas. Many of these chargers need to be high voltage fast chargers, especially along highways and for use by taxis and ride-hailing vehicles. In addition to the vehicles themselves, a range of new businesses are needed to own, operate, maintain, and manage charging infrastructure

In addition, hydrogen stations are needed to supply energy to fuel cell vehicles.

In the low carbon scenario, vehicle sales are 100% ZEV by 2040[2]. This rapid transition would need to be catalyzed by a combination of a more stringent ZEV mandate, buyer incentives, and deployment of public charging and hydrogen infrastructure. Policies such as support for used ZEVs and targeting of rebates and

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[2] This scenario element is not exactly aligned with the Governor's executive order (N-79-20) for 100% ZEV sales by 2035. This scenario was developed via independent research and so should not be viewed as incompatible with that goal. The accelerated ZEV side case analyzed does explore the emissions implications of a 100% ZEV sales by 2035 case.

infrastructure to DACs can ensure that the benefits of ZEVs will be spread more widely. (Figure EX-4 shows the percentage of light-duty vehicle sales shares made up of ZEVs, under the BAU and LC1 scenarios.)

To accelerate the purchase and use of ZEVs, more and stronger policies are needed that:

- Increase the sales mandate on automakers on a pathway to rapidly move to 100% ZEV sales
- Encourage consumers to buy ZEVs, with both monetary and non-monetary incentives, including the possible use of revenue-neutral feebates that encourage sales of ZEVs.
- Ensure that (subsidized) new and used electric vehicles are not leaving the state and that “used” gasoline and diesel vehicles are not being imported into California to circumvent ZEV policies.
- Encourage charging at off-peak times.
- Favor the purchase and use of ZEVs by underserved individuals and overburdened communities

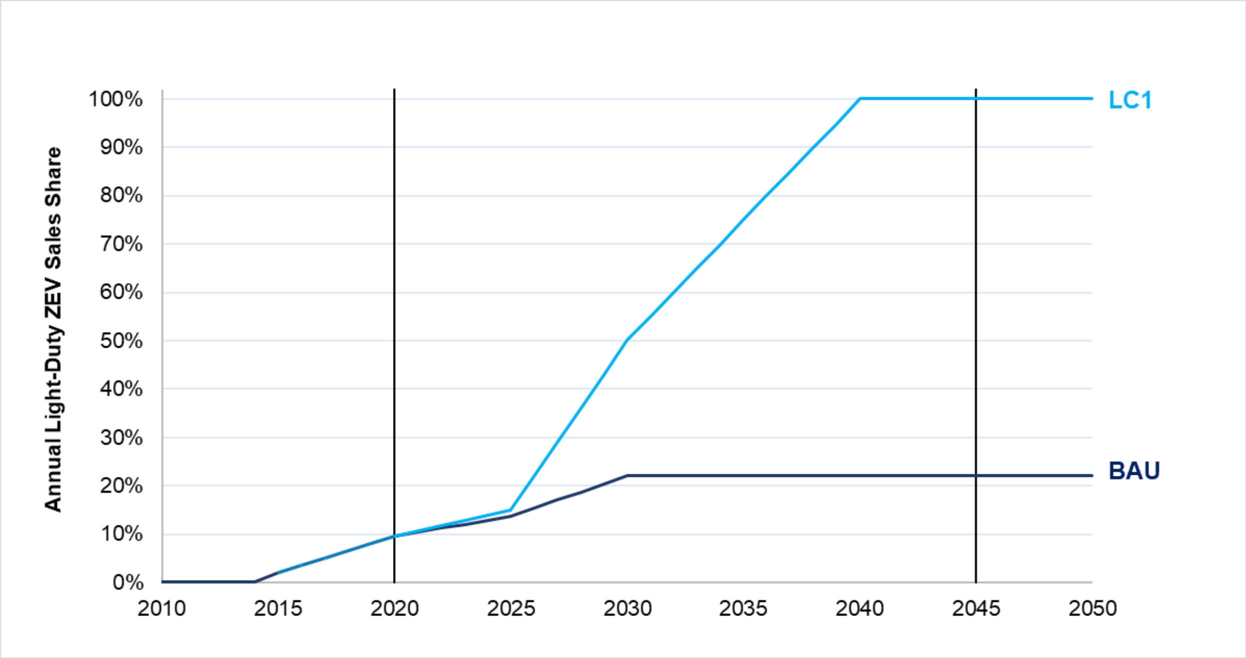

Figure EX-4. Annual Light-Duty Vehicle Sales, projected out to 2050 according to the BAU scenario and LC1 scenario. In the LC1 scenario, sales of ZEVs, (including BEVs, PHEVs, and FCVs) increase rapidly post-2025 to reach 100% of new vehicle sales by 2040.

Medium- and Heavy-Duty Vehicles

Medium- and heavy-duty vehicles in California (primarily for freight and business uses) are currently responsible for 20.6% of transportation emissions in the state. These vehicles are much more diverse than light-duty vehicles, ranging broadly in size from large pickup trucks to delivery vehicles to heavy-duty long-haul trucks. While the availability of vehicle models for zero emission medium- and heavy-duty vehicles has lagged behind light-duty vehicles, new zero-emission models that can serve this need are beginning to enter the market.

CARB in June 2020 adopted the first-ever standards in the world for zero-emission truck sales, known as the Advanced Clean Trucks rule. This rule is not included in the BAU scenario in this study because it was not a final policy at the time of analysis, but its successful implementation would be consistent with the needed rate of ZEV deployment to achieve large GHG reductions. CARB is also developing a corresponding demand-side fleet rule that would require larger fleets to purchase ZEV trucks. Figure EX-5 shows the percentage of heavy-duty vehicles made up of ZEVs, under the BAU and LC1 scenarios.

Key policy priorities for energy infrastructure for trucks include:

- State-funded charging stations for on-the-road charging of long-haul freight
- Continued California Public Utilities Commission-led reform of electricity pricing to make depot charging more affordable
- Research and demonstration of charging technologies and policies that provide grid services (such as real-time pricing, on-site storage, and bidirectional charging).

Key policy priorities for truck purchase and use are listed below. These policies need to be nuanced, to distinguish between trucks used for short versus long haul trips, the type of fuel they use, and even where they operate. These purchase and use policies should consider:

- Additional incentives, beyond the limited existing programs, to encourage fleet owners to purchase ZEVs. Consider combining incentive programs into a single program with integrated goals and balance the need for equity among fleets.
- Revenue-neutral feebates or the like that do not impose financial burdens on government and taxpayers, with some or all diesel truck buyers paying a fee and buyers of zero-emission trucks receiving rebates funded by these fees.
- Priority lanes and curb access for zero-emission trucks, which would encourage increased uptake, particularly if the effective hours for the priority lanes were well-chosen to optimize limited road space. Because of reduced noise from zero-emission trucks, night deliveries may be possible in more cities.
- Treating smaller class 2b and 3 trucks differently based on how they are used and by which industries, with PHEVs incentivized where trip lengths are long and/or uncertain, and BEVs incentivized where daily trips are shorter and/or more certain.
- Specialized treatment of construction and off-road trucks, including those used for agriculture, airport ground support, and cargo handling.

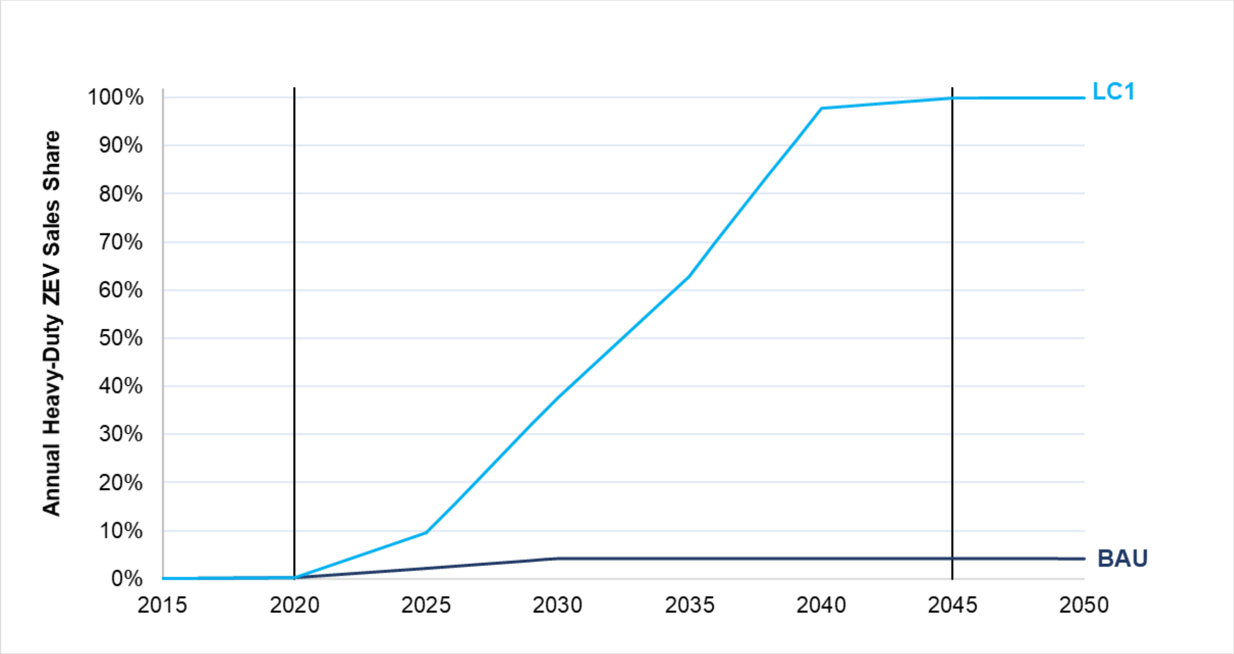

Figure EX-5. Zero-emission freight vehicle sales projected out to 2050 in the BAU scenario and the LC1 scenario. Sales of zero-emission trucks increase rapidly, following the implementation of the Advanced Clean Truck rule and subsequent deployment.

Vehicle-Miles Travelled (VMT)

In California, while transit, walking, and biking are important modes in many communities, most personal travel is by car, often with only the driver in the vehicle. Most communities have been designed around and for the car. The near-total dependence on personal motor vehicles leads to traffic congestion, pollution, and adverse health impacts, and the consumption of large amounts of public space for parking and roadways.

In recent years, California has worked to reverse this trend and introduce its communities to more modes and transportation choices. SB 375, passed in 2008, required each regional planning agency to submit a plan to reduce emissions, with a focus on reducing VMT. Agencies submitted plans that combined were intended to reduce emissions by 18% statewide. However, a key tracking report in 2018 found that VMT is increasing, not decreasing.

Some might say that VMT reductions are unnecessary because the use of ZEVs will eliminate all emissions from vehicles. But vehicle manufacturing emits large quantities of GHGs. Moreover, continued growth in vehicle use would contribute to myriad other land use, health, and safety concerns, waste large amounts of time of travelers, and incur large costs on transportation infrastructure. By also providing more transportation choices through a more diverse set of policies and systems, communities can improve their community health and increase accessibility to jobs, health, and other services, especially by underserved travelers.

Figure EX-6 shows the projected VMT under the LC1 and BAU scenarios. Because VMT reductions rely on changes in travel behavior and land use, which are slow to change (though the COVID-19 pandemic will likely accelerate the substitution of telecommunications for travel), the LC1 scenario only deviates significantly from the BAU scenario starting in 2030. In the LC1 scenario, VMT per capita drops somewhat through 2030, but not enough to offset population growth. After 2030, absolute VMT reductions result from significant changes in travel behavior, densification of land uses, more and safer bike and scooter use, better public transportation, and incentives to share rides. Even greater reductions would be possible if pooled automated ridesharing services were to proliferate, but these were not considered here. These VMT reduction strategies would offer more benefits in terms of community access and health.

To substantially reduce VMT by 2045, various public policies need to be extended or enacted to reinforce the travel behaviors and create the other changes that are needed. This study divided possible VMT reduction opportunities into groups of specific strategies. These policy strategies are grouped into the following categories:

- Built environment and land use changes:
    - Prioritize maintenance and avoid or cease new road building or road expansion.
    - Transit-oriented development/densification
    - Active transportation
    - Public transit investments, expansion, and incentives
- Transportation pricing:
    - Gasoline taxes
    - Shift to VMT-based road fees as the number of ZEVs grows and fuel tax revenues decline
    - Corridor congestion pricing and high occupancy toll lanes
    - Dense urban area cordon pricing
    - Parking pricing policies
- Transportation demand management (TDM) strategies:
    - Employer-based policies that encourage telecommuting
    - Employer-based carpooling policies that reduce subsidies for parking and encourage the use of transit, carpooling, and other modes
    - Incentives for the use of telehealth
- Micromobility and shared mobility:
    - Incentivize the use of walking and scooters by providing safer and better infrastructure and supporting companies offering bike and scooter services
    - Encourage the use of pooled and shared services by transportation network companies (e.g., Lyft, Uber, Via), including the eventual use of pooled, highly-automated vehicles
- Ensure that highly automated vehicles, which have the potential to increase VMT and reduce equity, are pooled and electric

The LC1 scenario includes VMT reduction that could be met from a variety of different specific combinations of strategies. The project team estimates that most of the above strategies will need to be implemented in concert to achieve the 15% reduction in per-capita VMT in 2045 from a 2019 baseline. This VMT reduction is included in the LC1 scenario, with somewhat further reduction possible through deeper implementation of pricing and land use policies that are complemented with improved transit, pooling, and micromobility solutions.

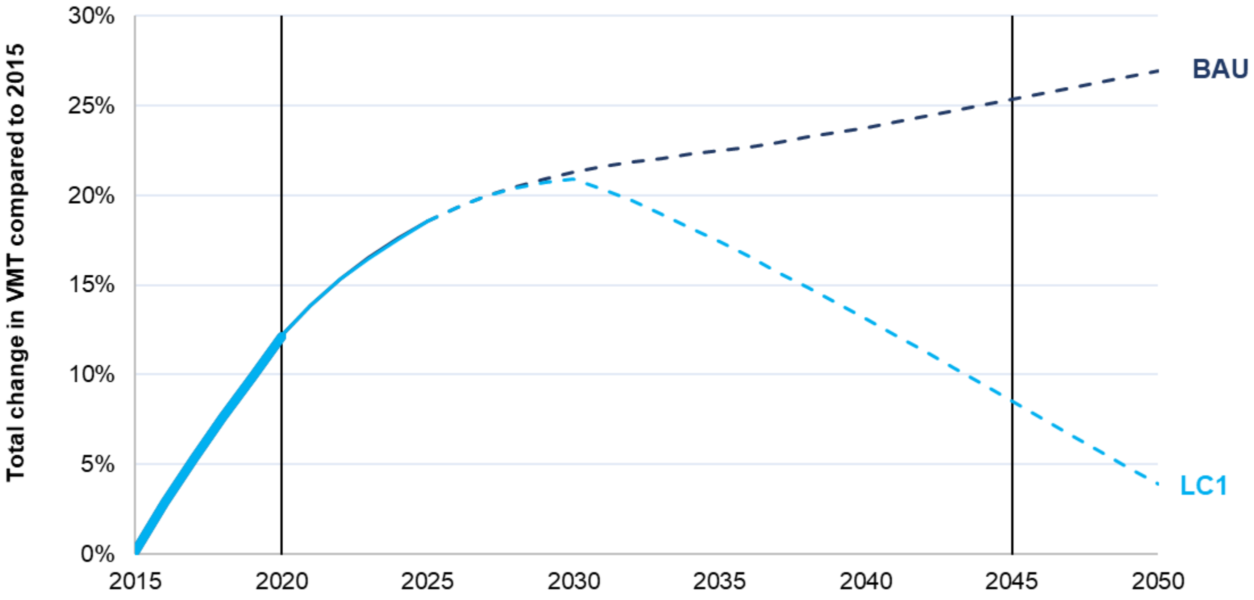

Figure EX-6. Change in VMT as compared to 2015, projected to 2050 according to the BAU scenario and the LC1 scenario

Fuels

Transportation in California, as everywhere in the world, is predominantly reliant on liquid petroleum fuels—gasoline for light-duty vehicles, diesel for trucks and ships, and kerosene-based jet fuel for most aircraft. While the state has seen significant growth in electricity and lower carbon biofuels, the transportation fuel mix is still 86% petroleum, on an energy basis [1]. Electricity and hydrogen are the key fuels for decarbonizing on-road vehicles in the LC1 scenario, but significant growth in low carbon liquid fuels compatible with internal combustion engines is still essential to meet the residual demand in these modes in addition to the demand for hard-to-electrify modes such as aviation and marine applications.

The primary policy affecting fuels in California is the Low Carbon Fuel Standard (LCFS), which requires that the average carbon intensity of transportation fuels declines over time. It analyzes emissions on a full life cycle basis, from raw materials production to use in the vehicle, in a technology-agnostic, market-based framework. To date, the LCFS has successfully supported a significant shift away from petroleum to lower-carbon alternatives and is well-positioned to continue doing so through the mid-2030s at least. As the transition towards a carbon neutral transportation system progresses, it may be necessary in the 2030s and beyond to update the LCFS to focus on the most critical challenges and fuels, particularly the development of very low-carbon liquid fuels to replace part or all of the petroleum gasoline consumed by the residual conventional vehicles during the last phase of the transition to zero-emission transportation. CARB will need to work with stakeholders to achieve a balance between protecting early investments in low carbon fuel supply capacity and minimizing support to fuels which may struggle to keep up with the pace of decarbonization in later years.

Policies to support the development of very low carbon liquid fuels should draw from the lessons learned during the decade of experience with the LCFS: policies should set ambitious, but achievable performance standards for the desired application and create a framework for evaluation and incentives. The state should not try to pick technological winners, but instead clearly define the desired characteristics of fuels and provide support for those that can achieve both short- and long-term goals, until they are competitive in the market on their own. It is also critical that emissions reductions in transportation not interfere with the ability of other sectors to meet their own decarbonization targets. For example, renewable natural gas (RNG) can be a low carbon vehicle fuel, but it may be in greater demand as a low carbon heating fuel or chemical feedstock. There are numerous potential specifications for a compliant fuel, including but not limited to the following:

- Compatible with existing spark-ignition engines, without voiding the warranty or compromising performance.
- Life cycle carbon intensity below a certain threshold, e.g., 25 g CO2e/MJ on a well-to-wheels basis.
- Plausible capacity to reduce carbon intensity to meet long-term decarbonization targets, e.g., 5 g CO2e/MJ or less by 2045.
- Does not significantly increase the emissions of criteria pollutants, toxic air contaminants, or any other pollutant.
- Meets strict sustainability criteria, with minimal indirect land use change impacts.
- Ability to be produced at scale, without compromising the ability of other sectors of California's economy to decarbonize.

Policies to develop supplies of fuels capable of meeting these targets could take any of the following forms, or a combination thereof:

- Mandated blending levels that complement LCFS requirements
- Creation of "Very Low Carbon" LCFS credits
- Loan guarantees and capital or permitting assistance for developers of compliant fuel production capacity
- Targeted incentives such as a volumetric credit, a competitive prize, an advance market commitment, or a contract-for-difference between the cost of very low carbon fuels and conventional ones.

The modeling conducted in this study indicates that by the mid to late 2030s BEVs will be cost competitive on their own merits and their rapid growth could generate enough credits to significantly drive down the LCFS credit price, depriving fuels critical to achieving the 2045 target of the incentives necessary for success. A reorganization of the LCFS will likely be necessary, with one possible solution being the phased removal of electricity as a credit generating fuel in the mid to late 2030s and early 2040s. Potential policy mechanisms for the gradual withdrawal of EVs from the LCFS program include (but are not limited to):

- Phase-down of credit generation per vehicle by a set fraction each year
- Adjusting the fuel displacement value for EVs to be based on the fraction of EVs in the fleet of a given vehicle type
- Freezing carbon intensities for EV charging at the model year of the vehicle to create a very predictable decline in LCFS credits generated on a per-vehicle basis, with a predictable date for the cessation of credit generation.

While not the focus of this study, transportation electrification also creates risks and provides an important opportunity for the electric grid. In some cases, upgrades will be needed to transmission and distribution to serve the load for charging. On the other hand, EVs will be an important source of flexible load and potentially on-demand battery storage. State policy and planning should seek to leverage EVs as a grid resource and incorporate them into demand planning.

Under every scenario examined by this study, there are some residual GHG emissions from fuels in 2045 (Figure EX-7), largely from liquid fuels used in older conventional vehicles or specialized applications. Unless a cost-competitive, highly-scalable zero-carbon solution emerges to meet this demand, California will need some negative emission or carbon sequestration capacity to counteract these emissions—if it expects to reach net-zero emissions in the transport sector. This could come from carbon capture and sequestration (CCS) projects, possibly using direct air capture to pull carbon dioxide out of the air and store it underground. CCS can also be combined with bioenergy, biofuel, or bioproduct systems to yield a system which removes more carbon from the air than it emits over its full life cycle (resulting in "net-negative" emissions). Another alternative would be sequestration by natural or working lands. In all, about 4–5 million metric tons per year of negative emission capacity will be needed in 2045, in addition to any CCS or negative emission projects that are part of a fuel production system, such as enhanced oil recovery or sequestration of carbon from ethanol production. Additional net-negative CCS capacity could increase the effective carbon budget, allowing greater consumption of non-zero carbon fuels while still achieving carbon neutrality.

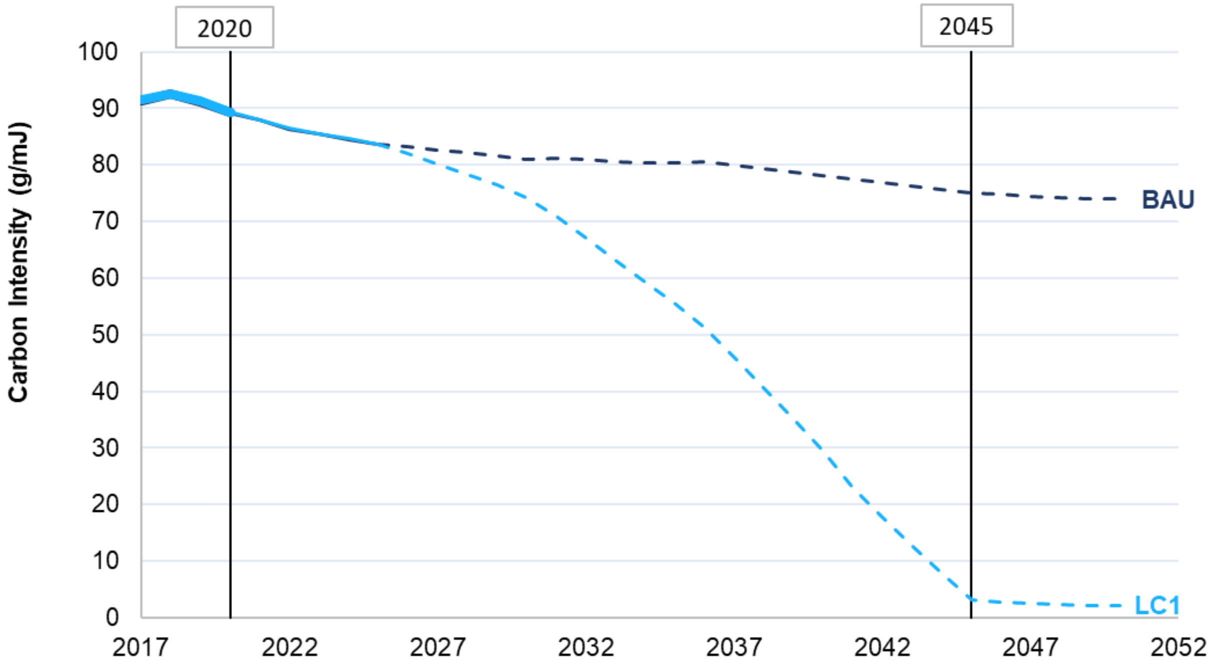

Figure EX-7. Carbon intensity of transportation fuels projected to 2050 according to the BAU and LC1 scenarios

Benefits and Impacts

Health

Transportation is a major cause of air pollution, which directly harms human health. The most damaging pollutants from California's current transportation system are particulate matter (PM) and nitrogen oxide compounds (NOx). High PM concentrations lead to lung and cardiovascular damage. NOx is a precursor to ozone and contributes to poor regional air quality. This study includes a detailed analysis of the localized health benefits of the shift to cleaner transportation modes, including the LC1 scenario elements in vehicles and VMT changes. The largest impacts are from cleaner heavy-duty vehicles, which are significant sources of pollution in many of the most vulnerable communities.

The low carbon scenario also dramatically reduces emissions statewide. The analysis finds that health benefits from reductions in particulate matter would be more than $28 billion dollars in 2045.

Equity

The transportation system in California has a legacy of inequity and of specific damage to DACs. Highways have historically been built through DACs with relatively little voice given to the people displaced. Entire communities have been divided by impassible freeways that cast a literal and economic shadow on adjoining areas. Our best understanding of the social determinants of health is as follows: Place (where a person is born and lives) is the most important factor in many outcomes and transportation related emissions and the presence or absence of transportation systems themselves in those locations are major components driving inequitable health outcomes.

California has been a leader in addressing equity and is committed to using decarbonization policy to further improve equity in the state. In 2012, the state required that at least 25% of cap-and-trade expenditures must be used to benefit DACs (as defined by the CalEnviroScreen tool). In 2017 the state increased that requirement to 35%. CARB estimates that 39% of cap-and-trade expenditures have occurred in DACs and have benefited DACs.

Given transportation's damaging legacy, the state should prioritize equity in its transportation investments and policies. In this report, most equity recommendations are embedded in the sector-specific analysis. These include, for example:

- In general, prioritize bringing disproportionate benefits to DACs first.
- For light-duty vehicles, continue to support incentives that are targeted to lower income buyers. Ensure deployment of charging infrastructure in multi-unit dwellings.
- For heavy-duty vehicles, prioritize electric vehicle deployment in DACs, for example by replacing drayage trucks and other trucks that disproportionally emit in DACs.
- In all VMT-related policy, prioritize policies that increase accessibility but avoid displacement. Focus on supporting transit and other low-carbon services and modes in DACs. In general, and especially for any road projects, prioritize input from affected residents and communities. Consider reverting historically damaging road projects such as elevated highways to more positive uses.
- For fuels, avoid siting fuel production facilities in DACs and carefully monitor local pollutants.

Workforce

Because transportation and associated industries are major employers, the transition to zero-carbon transportation will have significant effects on jobs and the workforce. Lower expected expenditures on some aspects of transportation mean that several traditional work areas, including vehicle maintenance and conventional fueling infrastructure, will see significant disruption.

New jobs will be created in areas like clean vehicle manufacturing and in electric and hydrogen fueling infrastructure. Many will be high-quality jobs and accessible without a college degree.

This analysis was specific to the transportation sector and did not estimate the indirect benefits of consumer savings being reinvested in the economy. These savings—driven largely by the significant advantages of ZEVs in terms of fuel efficiency and reduced maintenance costs—are substantial, exceeding $20 billion annually in 2045 compared to current conditions.

In some industries, such as automobile maintenance, job skills can carry forward with normal skill expansion. Other created jobs will require different skill sets compared to disrupted occupations. Workforce policy should be framed around a just transition for workers whose jobs are disrupted and creating employment pathways that allow for equitable access to jobs in growing ZEV-related industries. Policy can also help ensure that created jobs are high quality and empowering.

Benchmarks

One of the goals of this study is to provide a set of 'benchmarks' for the state to evaluate progress every 5 years between now and the goal year of 2045. These benchmarks are combined from key elements of the LC1 and underlying research. They show the key technological and policy steppingstones to meet the scenario targets. They can be used as a point of reference to track progress. They will need to be updated regularly as the transportation system evolves.

Table EX-1. Benchmarks for each transportation metric according to 2045 net zero goal

Subsector	2025	2030	2035	2040	2045
Sector-wide emissions (MMT CO_2e)/reduction from 2015	212 (4%)	166 (25%)	105 (53%)	53 (76%)	Zero carbon
LDV (% of new sales are ZEV)	15%	50%	75%	100%	
HDV (% of new sales are ZEV)	10%	38%	63%	98%	100%
VMT (per-capita VMT reduction from 2019 baseline)	4.8%	8.5%	9.9%	12.5%	15%

Subsector	2025	2030	2035	2040	2045
Fuels	Biomass based diesel <30 g/MJ average CI	500 mm gal/yr of <20 g/MJ drop-in gasoline 600 mm gal/yr of <25 g/MJ drop-in SAF	Petroleum fuels < ½ of total 500,000 tonnes/yr net-negative CCS	2 billion gal/yr of <12 g/MJ drop-in gasoline 0 petroleum diesel	2 billion gal/yr of <7 g/MJ drop-in gasoline 4 million tonnes/yr net-negative CCS
Workforce	Estimated annual full-time equivalent jobs in ZEV-related sectors exceed 100,000.			Projected annual expenditures on EV charging infrastructure reach nearly $9 billion.	Estimated annual full-time equivalent jobs in ZEV-related sectors exceed 500,000.

Table EX-2. Battery, vehicle, and charging benchmarks

	2025	2030	2035	2040	2045
Battery price (for LDVs)	$157/kWh	$107/kWh	$87/kWh	$87/kWh	$87/kWh
Vehicle Availability	Mid- and long-range passenger trucks become available	50% of new vehicle sales will be BEV, PHEV, or FCEV for all segments		100% of new vehicle sales will be BEV, PHEV, or FCEV for all segments	
Daytime Charging	Daytime Preference (DP): 0% Price: $0.20/kWh	DP: 20.6% Price: $0.12/kWh	DP%: 41.2% Price: $0.12/kWh	DP%: 61.8% Price: $0.12/kWh	DP%: 82.3% Price: $0.12/kWh
Infrastructure (single charging points for a 27 million vehicle fleet) H=home charging M= multi-unit developments W=workplace P=public	H: 1,000,000 M: 50,000 W: 40,000 P: 140,000	H: 2,660,000 M: 210,000 W: 410,000 P: 450,000	H: 4,460,000 M: 710,000 W: 1,500,000 P: 1,130,000	H: 6,172,000 M: 713,000 W: 3,534,000 P: 2,183,000	H: 7,310,000 M: 2,160,000 W: 5,770,000 P: 3,030,000

Conclusion

The primary conclusion of this research is that there are practical technologies and policies that could support the transition to very low or zero net carbon transportation by 2045 for California. This transition can also be accomplished in a way that is equity-centered, delivers benefits disproportionately for historically disadvantaged communities and groups, improves health, and creates hundreds of thousands of jobs.

These possible futures face formidable challenges, however. For the state to successfully shift to a zero-emission transportation system will require both urgency in terms of taking actions soon and a long-term perspective. This analysis finds that the transition depends on a major upfront investment in clean transportation, which can then pay off in terms of reduced costs and higher benefits. A comprehensive policy will also take into account both supply and demand for each subsector. In light-duty vehicles, this includes supply-side sales requirements and demand-side incentives. For medium- and heavy-duty vehicles, this includes a supply-side sales mandate and demand-side fleet purchase rule, as well as early-market incentives. The state also has a major role to play in fuel supply infrastructure, both for electric vehicle charging and hydrogen fueling.

There are also many open research questions that this report does not answer. The policy approach taken by the state should acknowledge uncertainty and support flexibility should technologies develop more—or less—rapidly than expected. The state should regularly (at least every five years) perform a similar comprehensive study of the current state of and future prospects for a zero-carbon transportation system and be prepared to adjust its policies as appropriate. This should be accompanied by a consistent investment in transportation research to improve our understanding of the sector, technologies, and policies.

Contents

1 Background

1.1 Current Policy Context

1.1.1 Overall

California has a long history of environmental protection relating to vehicle emissions. California was the first state to regulate emissions from motor vehicles, and California researchers played an instrumental role in advancing the science of air pollution. When the federal government passed the Clean Air Act Amendments in 1970, which created most of the air-pollution-control policy that protects Americans today, California was granted a special position of leadership, allowed to push its air-pollution-control measures ahead of the rest of the country. Other states were also empowered to follow California's lead.

California was also the first state to take comprehensive action on climate change. California adopted tailpipe GHG emission standards in 2003, followed by the Global Warming Solutions Act (AB 32) in 2006. The latter policy established a comprehensive portfolio of climate policies and required GHG emissions to be reduced to 1990 levels by 2020. This made California a global leader in climate policy. Several policy measures adopted under authority granted by AB 32 have direct impacts on transportation. This authority was extended in 2017 by the passage of SB 32, which committed the state to continue reducing emissions: specifically, to achieve a 40% reduction in GHGs from 1990 levels by 2030.

SB 498 directed CARB to review the effectiveness of its programs to increase the adoption of ZEVs in all sectors, and to make policy recommendations to increase the use of ZEVs for personal use and in fleets, which resulted in a report released in December 2019. The report noted that the Federal government is backsliding in vehicle emissions, VMT is increasing, and will require an aggressive approach to meet its GHG emissions reduction goals. It also emphasizes the need to improve ZEV penetration. The report reviews 28 ZEV regulatory, incentive, and supporting programs [2].

Based on the lessons learned from the programs, CARB lays out recommended policies in detail through the following:

1) Incentives and pricing strategies,
2) Lower fuel costs,
3) ZEV refueling infrastructure,
4) Local policies,
5) Fleet adoption,
6) Outreach and education,
7) Technology incubation and workforce development, and
8) Program flexibility.

The report ends with recommendation for California fleets to convert to ZEVs. These are summarized as: "assess fleet needs, research zero-emissions options, collaborate with stakeholders, develop and implement a strategic plan to acquire and utilize ZEVs, share your ZEV fleet experiences."

On September 23, 2020, Governor Gavin Newsom signed an executive order setting a goal that the state will mandate 100% ZEV sales in for passenger vehicles by 2035 and medium and heavy duty trucks by 2045 [3]. The order directs CARB to lead the development and proposal of the implementation plan. Although this report was written prior to Executive Order N-79-20, a final analysis of the impacts of this new and aggressive order will be included.

The California Energy Commission has also invested up to $100 million per year in funds to help achieve California’s emissions reduction goals through their Clean Transportation Program, which funds projects for electric and hydrogen vehicles and infrastructure, medium and heavy duty vehicles, biofuels, and workforce development [4].

1.1.1.1 Cap and trade

California’s cap-and-trade program—the first in the nation economy-wide program covering GHG emissions—is at the heart of the state’s climate policy. The cap-and-trade program works by requiring permits to emit CO2. Any major emitter of carbon (or distributor of fuels which would emit carbon when burned) must surrender enough permits at the end of every compliance period (typically three years) to cover their emissions. Permits are auctioned on a quarterly basis and can be freely traded once issued, which creates an effective carbon price. Emitters must acquire permits to cover their emissions and can sell excess permits if they reduce their emissions. Certain industries, including utilities and those deemed as risk of economic competition from industry outside of California (including petroleum refineries) are provided freely allocated permits to minimize emissions leakage or in the case of utilities, to benefit California ratepayers. Industry does not receive allocation to cover all emissions and must either buy permits and/or reduce onsite emissions. Cap-and-trade revenue is reserved for a specified set of uses. Utilities return the majority of revenue to ratepayers as yearly rebates from sales of permits the utilities are allocated. Revenue from state-owned auctioned permits is used to fund a variety of transportation and energy projects, including high-speed rail project, construction and operation of public transit, expansion of affordable housing, PEV rebates, and others.

1.1.2 LDV

1.1.2.1 Greenhouse gas emission standards

The Clean Air Act grants waivers for California to set state vehicle emission standards that are more stringent than those set by the federal government. In 2012, the Obama administration, together with California, adopted aggressive new GHG standards, linked to new Corporate Average Fuel Economy (CAFE) standards. To meet the new GHG and CAFE standards, light-duty vehicles sales would have had to achieve an average fuel economy of 54.5 miles per gallon (mpg), and the equivalent GHG emissions, by 2025. The Trump administration rolled those GHG and fuel-economy rules back in the Safer Affordable Fuel Efficiency (SAFE) Act, and formally revoked California’s waivers under the Clean Air Act. The Biden administration is undoing the SAFE rule and restoring California's waiver authority. Meanwhile, officials in California negotiated with five automakers to meet the standards that are not as strict as the GHG standards adopted in 2012, but are stricter than the SAFE standards.

1.1.2.2 ZEV mandate

The ZEV mandate has been the most important policy driver of zero and low-emissions vehicle sales in the last decade. The ZEV mandate was first implemented by California and has since been adopted by eleven other states as of 2020. The ZEV mandate works using a credit trading structure through mandates for automakers, requiring a minimum number of ZEV credits. Automakers are required to sell a minimum percentage of ZEVs, which increases each year. Automakers that cannot meet the requirement can purchase credits from other automakers to exceed the minimum percentage. For instance, Tesla sells 100% ZEVs, so they inevitably have credits to sell. The ZEV mandate forced automakers to begin EV design and development, which has spurred new technologies and led to the emergence of American EV companies like Tesla and Rivian [5].

1.1.2.3 Clean Miles Standard

2018's SB 1014 established the Clean Miles Standard, which requires TNCs to track and be accountable for their emissions. CARB is tasked with developing and enforcing the regulation, which has evolved into a GHG emissions per passenger mile standard. TNCs will be able to meet the standard by supporting electrification of their vehicles, increasing occupancy, shifting passengers to shared micromobility, or a combination. Questions still remain about ways to implement this regulation without disadvantaging TNC drivers, who are responsible for obtaining their own vehicles, as well as negatively impacting riders, especially those who are low-income, due to increased prices.

1.1.2.4 Incentives

Consumer incentives have spurred PEV purchases and demand. Federal and state purchase incentives help offset the higher upfront cost of PEVs. The stacking of these incentives can provide tens of thousands of dollars back to the consumer.

The Clean Vehicle Rebate Project (CVRP) was created by AB 118 in 2007. Eligible new vehicles and incomes (BEVs, and FCEVs) are eligible for up to $7000 in rebates on a purchase or lease. The CVRP has received $1.18 billion in funds from the GGRF and has allocated $682 million to eligible consumers [6]. Other incentives can be stacked depending on income and vehicle eligibility.

Under its original implementation, CVRP rebates were concentrated to a large number of high-income individuals who could afford to purchase a PEV without an incentive. As a result, in 2015, SB 1275 required CARB to develop additional transportation equity programs using GGRF funds. In 2016 CARB implemented an income cap for the CVRP program, and lower income applicants were eligible for an increased rebate amount[3] [7]. When combined with the federal tax incentive program, consumers are eligible for up to $7,000 for FCEVs, $12,000 for BEVs, and $11,000 for PHEVs).

It can be burdensome to apply to and wait for rebates for several months. Another incentive program, the Rebate Now program is piloted in San Diego, where drivers can be pre-approved to apply the rebate directly to the vehicle purchase instead of waiting until they apply for a rebate.

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[3] The income cap was reduced in 2016, and is currently $150,000 for single, and $204,000 for head of household, $300,000 for joint filings.

Non-monetary incentives have also been implemented, such as HOV and HOT lane access through the Clean Air Vehicle (CAV) program, and free or reduced parking in city centers. Lower income households are eligible for both the CVRP rebate and the CAV program, but higher income households must choose one of the two programs.

1.1.2.5 Equity Programs

Clean Cars 4 All is a program funded with GGRF money that gives financial incentives to lower-income households to retire ICE vehicles and replace them with new or used hybrid vehicles, ZEVs, or other mobility options, and install EVSE equipment and installation. The program offers up to $9,500 towards the purchase of a new vehicle, or $7,500 in incentives or alternative mobility options and can be stacked with CVRP rebates. Unlike CVRP, used vehicles are eligible for this program. Income eligibility is dependent on which air district residents live in, are operating in the South Coast, San Joaquin Valley, Bay Area, and Sacramento region. This income cap was recently extended to electric bicycles in participating districts. When CVRP is stacked with Clean Cars 4 All, consumers can receive up to $16,500 from California programs for the purchase of a FCEV [8].

CARB has also implemented programs providing financing assistance, like the Clean Vehicle Assistance (CVA) Program for income eligible buyers for new and used vehicles. The CVA program provides financing assistance and grant money to eligible purchasers. This can be combined with the CVRP program for eligible drivers, although eligibility is different for each program. CARB is partnering with GRID Alternatives and the Greenlining Institute to streamline all of the available incentives to low-income consumers, to help increase awareness of the programs available to them, and expanding education and outreach efforts [9].

CARB has developed the several clean mobility projects and car sharing projects throughout the state, including the Clean Mobility Options Project for organizations to develop a clean mobility program. The program provides vouchers to support zero-emission ridesharing, bike-sharing, and innovative transit. Agencies can apply for up to $1 million in voucher funds that will cover costs of vehicles, infrastructure, planning, outreach, and operations. Eligible organizations are non-profits, public agencies, and tribal authorities [10].

1.1.2.6 Infrastructure Funding and Goals

In 2012, Governor Brown issued Executive Order B-16-2012, which implemented a goal to deploy 1.5 million ZEVs by 2025 and directed several state agencies to ensure readiness of supporting infrastructure [11]. This effort has been led by the CEC. SB 350 and SB 32 have since further supported efforts for ZEV infrastructure. This legislation collectively aided the installation of 14,000 public chargers by 2017. In 2018, Governor Brown signed executive order B-48-18 which requires infrastructure for the adoption of 5 million ZEVs by 2030, including 200 hydrogen stations, and 250,000 chargers, including 10,000 DCFCs [11], [12].

AB 1236, signed in 2015 by Governor Brown, requires streamlined permitting to approve electric vehicle charging stations [13]. The Governor’s office has compiled a guidebook for electric vehicle permitting [14] and hydrogen permitting [15]. These resources will help encourage the installation of EVSE to meet the needs of California’s EC goals by 2035, buy reducing upfront costs for permitting and reducing permitting time through streamlining.

The signing of SB 1 in 2018 created the Road Maintenance and Rehabilitation Account (RMRA) and increased funding for transportation projects. SB 1 guidance states that Caltrans and cities and counties should fund “advanced automotive technologies” which includes charging and fueling opportunities for ZEVs. SB 1 also imposes a $100 fee on PEVs per year to compensate for the fact that PEVs pay little or no fuel taxes. Analysis indicates that PEV fees are not a sustainable funding mechanism for transportation goals [16].

1.1.3 HDV

Although only 7% of the vehicles on the road are medium and heavy duty, those vehicles account for 35% of the California’s NO_x emissions. HDVs are responsible for 22% of all emissions from the transportation sector.

1.1.3.1 Greenhouse Gas Emissions

The California Global Warming Solutions Act of 2006, Assembly Bill 32 (AB 32), established requirements for a comprehensive program of regulatory and market mechanisms to reduce GHG emissions in California. AB 32 also required CARB to develop and approve a Scoping Plan that describes California’s approach to reducing GHG emissions to 1990 levels by 2020. The Scoping Plan was first approved by the Board in 2008 and updated in 2014 and 2017.

The Tractor-Trailer Greenhouse Gas Regulation (TTGHG) was an early action measure from the 2008 Scoping Plan. The Board approved the TTGHG regulation in December 2008 which became effective January 1, 2010. This regulation reduces the GHG emissions from long-haul tractors and trailers by improving the aerodynamic performance and reducing the rolling resistance of tractor-trailers[17]. CARB also implemented the Smog and Particulate Rule, which requires a diesel particulate filter in vehicles made after 2014. Such filters cut PM emissions by 95% or more and curb other harmful emissions as well [18], [19].

In 2011, U.S. EPA and the U.S. DOT’s National Highway Traffic Safety Administration (NHTSA) jointly adopted the first-ever GHG emission standards and fuel economy standards for new medium- and heavy-duty engines and vehicles, the Phase 1 regulation. The Phase 1 regulation covers three categories of vehicles: tractors; vocational vehicles (including utility trucks, box trucks, and garbage trucks); and large pickups and vans. CARB harmonized with the federal Phase 1 standards beginning with 2014 model year.

In 2016, the U.S. EPA and the NHTSA adopted the second phase of the GHG and fuel-efficiency standards for new medium- and heavy-duty engines and vehicles, the Phase 2 regulation. The Phase 2 regulation built upon the Phase 1 regulation and established more stringent CO2 emission standards beginning with 2021 model year for medium and heavy duty vehicles except trailers. Phase 2 also introduced trailer requirements for the first time. In 2018, California largely aligned with the federal Phase 2 Regulation in structure, timing (except the initial trailer standards), and stringency, but with some minor California differences [20].

In December 2018, CARB adopted the Innovative Clean Transit Regulation (ICT) requiring all state transit agencies to transition to a 100% zero-emission bus (ZEB) fleet, also encouraging first and last mile connectivity. Beginning in 2029, new bus purchases must be 100% ZEB. Large transit agencies were required to submit a rollout plan by July 1, 2020, and small agencies are required to submit their rollout by 2023 [21].

1.1.3.2 Zero-emission trucks

CARB recently voted on July 25th, 2020 to approve the California Advanced Clean Truck Rule (ACT), which requires medium- and heavy-duty truck makers to manufacture and sell a minimum and increasing number of zero-emission trucks in California. Beginning in 2024, at least 9% of vocational trucks certified Class 4–8 need to be zero-emissions, and 5% of all other truck classifications, a percentage that increases each year. By 2035, zero-emission truck/chassis sales would need to be 55% of Class 2b–3 truck sales, 75% of Class 4–8 straight truck sales, and 40% of truck tractor sales. The ACT also contains a one-time reporting requirement, where large fleet owners (retailers, manufacturers, brokers, etc.) must report information about existing fleet operations [22].

CARB is also developing the Advanced Clean Fleets regulation that will set a target of zero-emissions truck and bus fleets by 2045 everywhere in California, with a earlier goal for short-haul applications like delivery trucks and drayage equipment [23]. This rule will be developed utilizing the fleet reporting requirement of the ACT, to help identify future strategies [22].

1.1.3.3 Incentives and programs

Multiple programs have been implemented through the California Climate Investments Program, including the Hybrid and Zero-emission Voucher Incentive Project (HVIP) includes the Clean Truck and Bus Vouchers program and the zero-emission truck and bus pilot. The Clean Truck and Bus Voucher program offers vouchers up to $315,000 to private and public operators for the purchase of zero-emission, plug-in hybrid, and certified to the cleanest optional low-NO_x standard trucks and buses. The zero-emission truck and bus pilot program grants funding to local air districts, transit agencies, school districts, and other public entities and non-profits to partner with technology providers.

Another example of CCI funds includes the Zero and Near Zero-Emissions Freight Facilities (ZANZEFF), which provides funding for reducing the emissions from goods movement by providing funding opportunities for industry partners working to develop zero-emissions technologies that can be adopted widely in the future [24]. Projects receiving funding were chosen in alignment with the Caltrans Sustainable Transportation plan [25].

Separately, the Carl Moyer Memorial Air Quality Standards Attainment Program (Moyer Program) has allocated approximately $1 billion in grant funding to date to reduce air pollution from older vehicles and equipment in California. The program was created in 1998 to fund cleaner-than-required heavy-duty engines, equipment and emissions reduction technologies and legislation (AB1571) have since established a framework for the program [26].

1.1.3.4 Freight and goods movement

Governor Brown signed Executive Order B-32-15 in 2015, calling for the development of a freight action plan to establish targets for freight efficiency, boost zero-emission technologies, and increase the competitiveness of California’s freight system [5]. Ships are the largest source of emissions in the Los Angeles and Long Beach ports, which disproportionately impact surrounding communities. Cap-and-trade funds are allocated to improve freight efficiency, especially in communities designated by CalEnviroScreen proximate to ports. Through working with CARB, the largest ports in the state have achieved an 80% reduction in PM emissions, a 90% reduction in SO_x emissions, and a 50% reduction in NO_x emissions since it was signed [27].

1.1.4 California policies related to VMT

The transportation sector is responsible for the largest share of GHG emissions, as discussed in previous sections. Passenger VMT has consistently increased for numerous reasons, including population growth and urban sprawl. A wide range of policy-related solutions could be employed to reduce per capita and total VMT in California as the state's population grows. Several current policies in the state related to VMT are discussed below. Extended and additional policies are being contemplated for inclusion in the future.

1.1.4.1 Sustainable communities

In 2008, Governor Schwarzenegger signed SB 375, California's Sustainable Communities and Climate Protection Act to help meet the goals of AB 32, California's Global Warming Solutions Act. Meeting SB 375 goals requires a coordination between transportation and land use on a regional scale is required to reduce GHG emissions from the transportation sector.

SB 375 requires each of California's 18 Metropolitan Planning Organizations (MPOs) to work with CARB to establish a GHG reduction target for 2020 and 2035 for each region; these targets must be updated, at minimum, every 8 years. Each MPO will adopt a Sustainable Communities Strategy (SCS) as part of their regional transportation plan, which details how each region will meet these targets. Bolstering existing housing legislation, SB 375 requires each MPO to coordinate their regional housing needs allocation with their SCS. CARB reviews each SCS and determines if the plan in place will meet the target requirements; if CARB decides the target will not be met through their plan, the MPO must prepare an Alternative Planning Strategy (APS).

Reducing VMT per capita will play a large part in meeting GHG-reduction goals outlined in SB 32. The Sustainable Communities and Climate Protection Act of 2008 (SB 375) directs CARB to set emissions-reduction targets. Specifically, MPOs must develop Sustainable Communities Strategies (SCSs) that recommend transportation, land use, and housing policies to reach regional emissions targets. In transportation, GHG-reduction policies include policies that guide transportation choices towards lower per capita VMT options [28]. Based on these metrics, SB 150 was passed in 2017 to require that CARB prepare a report for the legislature every four years to discuss the progress on SB 375. The first report was published in 2018 [29]. The most recent iteration of the report states that California is not on track to meet its VMT reduction goals, as VMT per capita continues to increase. Reducing emissions from transportation is required for the state to meet future GHG reduction targets, and other equity, economic, housing, and public health benefits are at risk.

In 2018, California's Natural Resources Agency implemented SB 743 to update CEQA guidelines. Specifically, SB 743 directed the Governor's Office of Planning and Research to evaluate alternatives to Level of Service (LOS) as a mechanism for evaluating the impacts of transportation and develop guidelines. California Natural Resources Agency implements the regulation process. Starting July 1, 2020, these quantitative measurements include VMT, VMT per capita, automobile trip generation rates, and trips generated. SB 743 was also amended to allow cities and counties to opt out of LOS standards in certain areas with infill development.

1.1.4.2 Bicycle and pedestrian modes

The Caltrans Active Transportation Program (ATP) was created in 2013 after passage of SB 99. The ATP aims to make California a national leader in active transportation. The program is managed by Caltrans and the California Transportation Commission and administered by the Division of Local Assistance, Office of State

Programs. The original budget for the ATP in 2013 was $123 million per year, of which $88.5 million comes from the federal government. 2017's SB 1 directed another $100 million per year to the ATP [30], [31].

Among other goals associated with the program (including increasing active mode shares, increasing safety for non-motorized travel modes, and improving public health), the ATP explicitly aims to support California's GHG-reduction goals related to 2008's SB 375 and 2009's SB 341. The ATP also funds the Active Transportation Resource Center (ATRC), which provides a wide variety of technical and non-technical documentation associated with active transportation projects.

1.1.4.3 Innovative mobility systems

The Clean Miles Standard (SB 1014) aims to lower per capita VMT by utilizing a GHG per PMT approach. CARB will regulate and cap GHG per PMT for TNCs, but is still working out details about cap enforcement, as well as equitable ways to implement the rule and distribute revenue. The cap will also apply to micromobility companies (e.g., companies supplying e-scooters and e-bikes). SB 1014 requires CARB to establish baseline emissions from TNC vehicles, as measured on a per-passenger-mile basis. This includes emissions from all stages of TNC vehicle operation, including periods 1, 2, and 3[4]. The legislation requires baseline emissions to be established for miles traveled via zero-tailpipe-emission modes including scooters, walking, and biking.

2019's SB 400, Reduction of Greenhouse Gases Emissions: Mobility Options, classifies bike-share and e-bikes alongside public transit and car sharing as a "cleaner and more efficient motor vehicle or a mobility option," and therefore allows those modes to be included in the Clean Cars 4 All program.

1.1.4.4 Funding

State and local governments can utilize funding to increase alternative transportation modes like transit and active transportation. In 2019, Governor Newsom signed Executive Order N-19-19 to redouble the state's efforts to reduce GHG emissions. Transportation is the only sector in California where GHG emissions have continued to increase, so one of the provisions of that executive order directed Caltrans to leverage more than $5 billion to reduce GHG for transportation through the California State Transportation Agency (CalSTA). This will better align infrastructure projects with climate goals, and through investment in transportation projects that support transit-oriented development, and supporting infrastructure for pedestrians and cyclists. For example, programs like the Affordable Housing and Sustainable Communities Program (AHSC) will help support climate goals through investment of GGRF money [32].

Fuel taxes are not only revenue sources, but can also influence travel behavior in ways that reduce VMT. SB 1 indexed the gasoline tax to inflation (raising it from 30 to 42 cents per gallon), increased vehicle-registration fees, and increased diesel fuel taxes. Investment priorities for additional funds will improve transit and active transportation infrastructure.

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[4] Period 1 (P1) is the period of time after a driver logs into a TNC application but is not yet matched with a passenger. During this time period, the driver awaits a ride request through the TNCs; Period 2 (P2) starts when a match is made and accepted by the driver, but before the passenger has entered the vehicle. During this period of time, the driver is en route to pick up the passenger; Period 3 (P3) begins when a passenger has been picked up and is an occupant of the TNC driver's vehicle. This period of time lasts until the driver completes the transaction (on the online-enabled application or platform), or until the ride is completed, whichever is later.

1.1.5 Fuels

1.1.5.1 Low Carbon Fuel Standards (LCFS)

The LCFS sets a declining target for the average carbon intensity of its entire fuel pool, assessed across the full fuel lifecycle (including the production of raw materials, conversion into fuel, transport to market, and consumption in vehicles). California fuel producers are required to comply with this target by reducing emissions from their fuels, blending in lower-carbon fuels, or buying credits from low-carbon fuel producers. Each LCFS credit represents one metric ton of emissions in excess of the required reduction for a given year.[5] Fuels that marginally reduce emissions receive a small amount of credit per gallon sold, while very low carbon fuels can receive much greater incentives. The intent of the LCFS is to create a strong incentive to support the deployment of new, low-carbon technologies while creating a market-based performance incentive for the deployment of currently available technologies. While some credits can be generated by improving the efficiency of existing refineries, shifting to lower-carbon alternative fuels is the most common mechanism to meet LCFS targets. The most common alternative to petroleum at present is biofuels, though electricity is rapidly growing as a vehicle fuel and will likely supply an increasing fraction of total fuel consumption in future years. The LCFS has significantly expanded the use of biofuels in California since it was implemented in 2011, increasing the fraction of non-petroleum fuel used in California from 7% to 16%, on an energy-content basis. At present, the LCFS offers around $200 per ton of emissions reduced and has made California one of the most attractive markets for alternative fuel producers.

1.1.5.2 Electricity Decarbonization (SB100)

Electrification of passenger vehicles, along with a significant fraction of medium- and heavy-duty vehicles, is a central pillar of California's long-term transportation decarbonization plan. While the superior efficiency of electric motors gives EVs a lower emission footprint per mile of travel under current conditions, the long-term decarbonization goals California has adopted cannot be met without a significant decarbonization of California's electric grid. California has primarily used an RPS, along with carbon pricing from its cap-and-trade program, to reduce emissions from its electric fleet. First adopted in 2002 as a result of SB 1078, the RPS requires a certain amount of California's retail electric sales to come from renewable sources, including wind, solar, geothermal and small hydroelectric projects. SB 1078 required 20% of California's generation to come from renewable sources by 2017. That target was extended in 2015 to a 50% requirement by 2030 under SB 350 and further by SB 100 to 60% by 2030. SB 100 additionally requires that eligible renewable energy resources and zero-carbon resources supply 100% of retail sales of electricity by 2045.

1.1.5.3 EV and FCEV Infrastructure

California has recognized the need to deploy charging infrastructure to support the transition to plug-in vehicles. In 2018, Governor Jerry Brown issued Executive Order B-48-18 which set targets for 250,000 EV charging stations, including 10,000 DC fast chargers to be deployed by 2025, as well as 200 hydrogen fueling stations. This

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[5] It is important to note that even though LCFS credits and cap-and-trade permits are both instruments that nominally represent one metric ton of emissions, they are not comparable or exchangeable for each other. Cap-and-trade permits represent a metric ton of CO_2 or equivalent. LCFS credits represent the reduction in life cycle emissions of a metric ton of CO_2 equivalent, compared to that year's standard. In practical terms, LCFS credits are typically more expensive than cap-and-trade credits, but the aggregate market for them is much smaller.

builds upon several existing state actions to expand the amount of EV charging infrastructure available, including grant and incentive programs from the CEC and charger installation supported by utilities using either rate-based revenue or the proceeds from sales of LCFS credits from residential EV charging.

SB 350 (2015, de Leon) helped set the landscape for EV charger installation, by making utilities, under the guidance of the CPUC, responsible for planning and managing the development of EV charging infrastructure sufficient to support California's long-term EV goals. It also supported the development of EV rate structures for electrical utilities, to support EV charging, encourage off-peak charging and protect EV users from the risk that charging could advance them into a higher cost tier under previously existing plans [148].

1.1.5.4 Fuel taxes

Fuel taxes in California, like the rest of the United States, are primarily a mechanism for funding road maintenance and improvements. Fuel taxes also intended to reduce the consumption of petroleum by increasing its price. The federal government imposes fuel excise taxes of 18.4 cents per gallon on gasoline and a 24.4 cents per gallon on diesel. These taxes were last adjusted in 1993 and are not indexed to inflation, which has caused the taxes to decline in real value over time. California adds a number of statewide fuel taxes including per-gallon excise taxes, sales tax, and price-based taxes. In 2017, state gas taxes were increased by SB 1. Gas taxes in California now total over 55 cents per gallon. Gas-tax revenue is expected to add over $50 billion dollars in total aggregate transportation funding over the next decade, narrowing the anticipated revenue-expenditure gap for transportation by about two-fifths.

1.1.6 Equity and environmental justice

Low-income and DACs are disproportionately burdened with the negative impacts from land development practices and transportation-generated pollution. California has enacted several laws directing funding to EJ communities and requiring EJ to be a consideration in planning. SB 1000, signed in 2016, requires local governments to identify EJ communities and address environmental inequities in various plans. In addition, CalEPA has developed a screening tool called CalEnviroScreen to identify communities that are disproportionately affected by several metrics related to pollution.

The Community Air Protection Program, AB 617, was established in 2017, requiring localities through local air agencies to reduce exposure to air pollution in the most impacted communities. The program includes incentives to deploy cleaner energy and more efficient technologies, requires retrofitting pollution controls on industrial sources, increased penalty fees, and increases transparency of emissions data [34].

Policymakers in California have also recognized the importance of EJ at the local and regional levels. For instance, SB 375 established cyclical planning processes in 18 regions with the goal of reducing GHG emissions and achieving state policy goals. Among other things, the Act's SCS requirement addresses a number of co-considerations, including social equity. Unfortunately, while each region has adopted an SCS plan, a 2018 CARB Progress Report on SCS milestones showed that California is currently not meeting its CO_2 emissions-reduction goals. VMT per capita is rising statewide. In the regions covered by California's four largest MPOs, commuting times have increased for both single-occupancy vehicles and public transit.

1.2 Other Impacts and Externalities

Pollution from transportation is a classic externality: the costs of the pollution are not paid by the person emitting it. However, there are many other externalities in the transportation system. Some are easier to quantify than others, but the damage is no less real.

Table 1.1 shows a list of the external costs of motor-vehicle use that will be affected by different transportation scenarios. We distinguish monetary from non-monetary costs because the former are already observed in monetary terms (dollars) whereas the latter must be converted to monetary terms via an additional valuation step. As a result, non-monetary costs are much more uncertain. We include non-monetary impacts of motor-vehicle infrastructure because long-run scenarios that dramatically reduce motor-vehicle use may affect the scale, configuration, and location of motor-vehicle infrastructure.

For the final report, we plan to quantify the external costs shaded in green: crash costs, oil-use costs, air-pollution costs, climate-change costs, and noise costs. That analysis will use a unified set of assumptions and methods to estimate air-pollution and climate-change costs. The methods and assumptions for that analysis generally will not be the same as those used in the detailed health-effects analysis presented elsewhere in this report. In the final report we will explain the differences between the detailed health-effects analysis and the less detailed but more comprehensive air-pollution external cost analysis.

Table 1.1. Monetary and non-monetary external costs of motor-vehicle use.

Monetary externalities	Nonmonetary externalities
• **Travel delay**, monetary costs imposed by others: extra consumption of fuel, and foregone paid work • **Crash costs** not accounted for by economically responsible party: property damage, medical, productivity, legal and administrative costs • **Oil use**, **macroeconomic adjustment losses** of GDP due to oil-price shocks • **Oil use**: **military expenditures** related to use of Persian-Gulf oil by MVs • **Oil use**: the annualized cost of the Strategic Petroleum Reserve (SPR) • **Oil use, pecuniary externality**: increased payments to foreign countries for non-transport oil, due to ordinary price effect of using oil for MVs^	• **Travel delay**, imposed by other drivers, that displaces unpaid activities • **Crash costs** not accounted for by economically responsible party: pain, suffering, death, lost nonmarket productivity • **Air pollution** **– road-dust, brake & tire wear** **– upstream emission** **– vehicle emissions** Effects on human health, crops, materials, visibility, ecosystems* • **Climate-change** due to life-cycle emissions of GHGs • **Noise** from MVs • **Water pollution**: leaking storage tanks, oil spills, urban runoff, road deicing • **Other externalities:** solid waste from motor vehicle (MV) use, vibration damages, fear of MVs and MV-related crime **Nonmonetary impacts of the MV infrastructure#** • **Land use change**: loss of habitat and biodiversity due to highways and other MV infrastructure • **Socially divisive effect of roads** as physical barriers • **Esthetics** of highways and vehicle and service establishments

MV = motor vehicle; GNP = gross national product; GHG = greenhouse gas; SPR = Strategic Petroleum Reserve. Areas shaded green will be quantified in the final report.

* The cost of crop loss, and some of the components of other costs of air pollution (e.g., the cost of medical treatment of sickness caused by MV air pollution), technically should be classified as monetary externalities.

Although these are nonmonetary environmental and social costs of total MV use, they are not costs of *marginal* MV use, and hence technically are not externalities.

^ Within a country, pecuniary externalities are transfers between entities and not actual net social costs. However, if the transfer is between countries, then there is a net loss to one country (which at the global scale is balanced by the gain to the other country). If one takes a country-perspective and thus counts the oil-use pecuniary external cost as a real cost, then for consistency one also should take a country-specific perspective with respect to climate-change damages.

2 Special Section: COVID-19 and Transportation

The novel coronavirus (COVID-19) global pandemic upended all aspects of life in California, and transportation has been no exception. This topic is evolving rapidly, so recent detailed data is challenging to come by. It will take years to develop a full understanding of the pandemic's effects. However, data from various sources has made some top-line impacts for California clear. First, travel fell dramatically as the state entered lockdown. Second, transit use was particularly hard hit, as most voluntary riders preferred to avoid shared spaces and agencies reduced service. Third, pollution from transportation fell—but not as much as might be expected since truck traffic continued largely unabated. Fourth, petroleum prices fell dramatically, sending prices for oil futures contracts negative for a brief period. Fifth, in markets that have begun to recover, car travel has returned much more rapidly than other modes. Sixth, transportation budgets (including for clean transportation programs) have been dramatically impacted in the short and medium terms.

2.1 Impacts

2.1.1 Impacts to travel amount

California entered a state of lockdown in spring 2020. Governor Newsom issued a statewide directive to stay home except for critical needs (such as travel to work for essential employees, grocery shopping, and time-sensitive medical appointments). The data show that people responded by traveling much less. Caltrans data shows 20% less travel volume for March 2020 compared to March 2019, and 40% less travel volume for April 2020. Technology companies with access to user cell-phone data such as Google similarly reported a dramatic reduction in travel statewide, with some of the most affected counties reducing shopping and workplace travel by more than 60% [35]. Underlying this was an unprecedented increase in unemployment and a major shift to work-from-home. Some companies have announced that they will make at least some aspects of their work-from-home policies permanent, which could also permanently affect transportation demand. However, research on telecommuting in general finds that workers often add other trips during their day, which could limit to benefits of telecommuting to emissions after restrictions lift.

2.1.2 Impact to transit, pooling, and other modes

All state transit agencies have faced enormous disruptions and drops in ridership. The California Transit Association reports [36] that some agencies saw ridership drop more than 90%. Large markets were amongst the hardest hit, including LA Metro (75%), San Diego Metropolitan Transit System (75%), Sacramento Regional Transit (80%) and BART (94%). While fares are only one source of revenue for transit agencies, reduced ridership is causing a revenue challenge and may erode public support if ridership numbers don't recover.

Federal stimulus programs included some support for transit. $3.7 billion of the $25 billion in federal funds that have been allocated to date to support transit in the wake of the pandemic were directed to California [37]. This temporary infusion of federal transit funding to the state helped mitigate short-term funding challenges for some agencies, however, the longer-term prospects for transit in the current policy environment are less clear and more support has not been forthcoming. There is also significant uncertainty as to riders' willingness to return to transit even though transit has not been a major vector in transmission in countries that have mostly recovered from COVID-19. Agencies are exploring options to increase user confidence as the economy reopens.

The pandemic's impacts on bicycling and walking are more complex. Many people are turning to these modes as a form of exercise during the pandemic, and some cities have closed streets to vehicles in order to supply more space for active transportation. However, these trips are unlikely to be a substitute for driving, and it is unclear how long-lasting these effects might be.

COVID-19 has also had a chilling effect on shared new mobility modes. Uber and Lyft both suspended their pooled-ride services. The longer-term impacts of COVID-19 on ridesharing is not yet known, though several research projects are underway to begin to evaluate the effect on traveler willingness to share space.

2.1.3 Impact on pollution and climate emissions

One of the major news narratives of the pandemic is the reduction in local pollution and CO_2 emissions due to sudden decreases in personal and economic activity. Air quality has indeed improved in many cities. Ozone, a pollutant produced from the combination of NOx emissions with VOCs, dropped 14% in the Los Angeles area.

The pandemic's effect on CO_2 emissions has also been significant at a global scale. A recent paper in *Nature* estimated that total daily CO_2 emissions fell by more than 15% compared to 2019 for the period of peak confinement. Surface emissions (36% reduction) and air-transportation (60% reduction) emissions were the most affected (Figure 2.1).

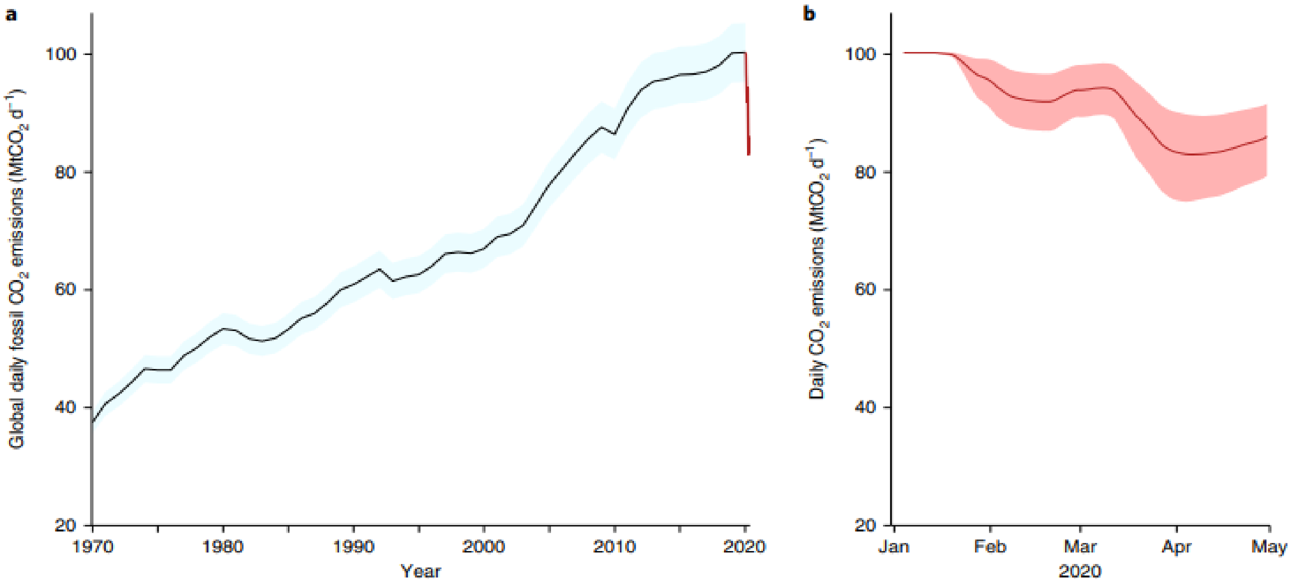
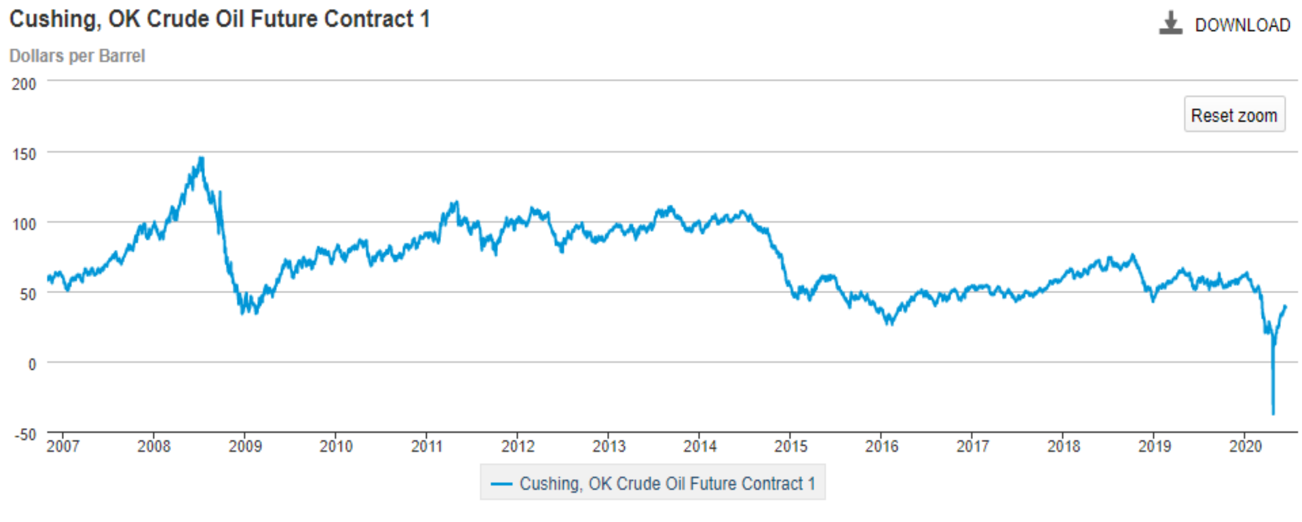


Figure 2.1. Impact of COVID-19 on GHG emission. From https://www.nature.com/articles/s41558-020-0797-x

2.1.4 Impact on petroleum prices

COVID-19 induced a drop in demand for gasoline and diesel at a time when there was already an oversupply in global oil markets due to ongoing geopolitical disagreements about supply cuts and flattening global demand. These factors together drove oil and petroleum prices sharply lower, and actually created a short-term period of negative prices in oil futures.

Low oil prices have several interacting effects. First, low prices and futures price uncertainties are creating economic challenges for energy companies (especially smaller companies) and have already led to several announced bankruptcies, including Whiting Petroleum and Diamond Offshore. At the same time, sustained low gas prices make driving cheaper and may make EVs and other alternative transportation modes less competitive (Figure 2.2).



Source: U.S. Energy Information Administration

Figure 2.2. History of crude oil prices (future contracts). Prices spiked and then fell in 2008 before and during the Great Recession. In 2020, futures prices fell suddenly and were briefly negative, in part due to reduced demand from COVID-19.

2.1.5 Data from recovering markets

A major policy question is what the recovery from COVID-19 in California will mean for activity, energy use, pollution, and emissions. If recovery is rapid, and people return to driving while avoiding transit, emissions will rapidly return to pre-pandemic levels. Early data from countries (such as China) and states and counties that have begun to reopen is cautionary: car travel has rebounded much faster than transit.

Yet some markets are linking the recovery from COVID-19 to positive changes in transportation. For example, France is coupling their recovery strategy with increased incentives for PEVs as part of the stimulus package. Many European countries are pushing bicycling and other clean transportation as a way to recover in a way that also contributes to fighting climate change.

2.1.6 Budget impacts

COVID-19 has created major deficits for California. Although California came into the year with a $5.6 billion surplus, Governor Newsom has announced an expected $54 billion deficit based on the latest state projections. This deficit will quickly burn through the state's "rainy day" fund. As of this writing, there is extensive discussion on how the state can develop a balanced budget as required by the state constitution. The budget situation means that funds for transportation incentives and other transportation programs are likely to be extremely limited for at least the next year.

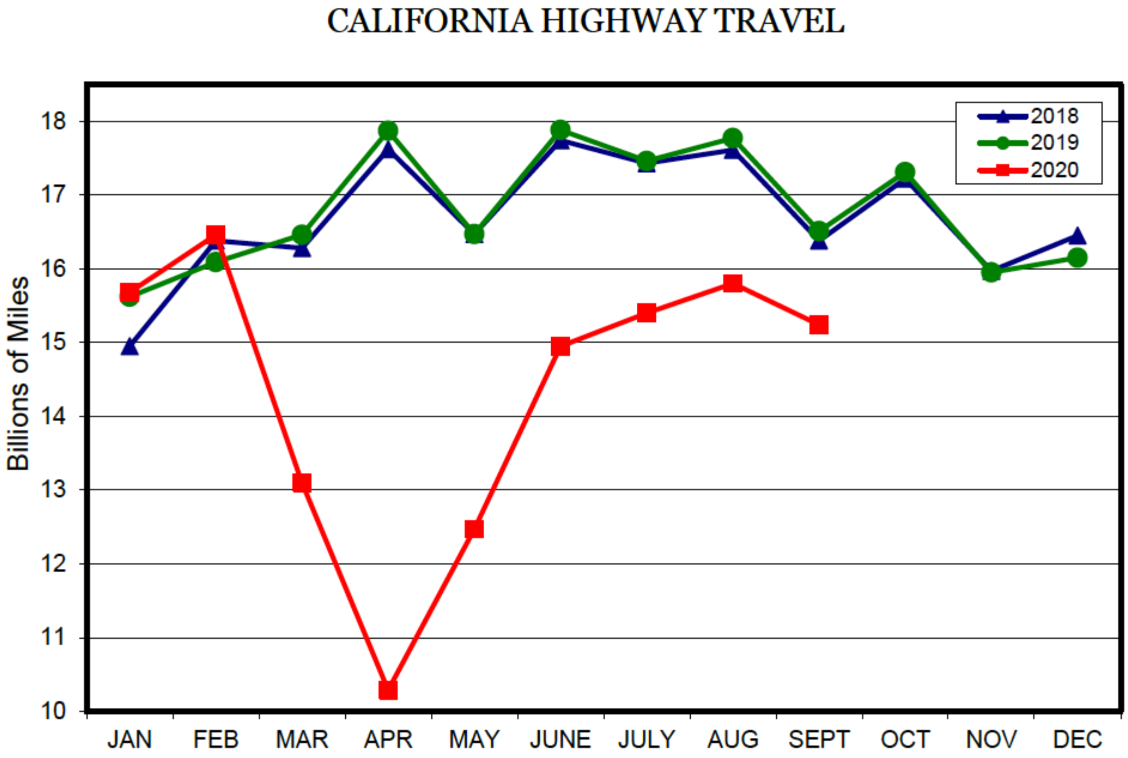


Figure 2.3. California Highway Travel (Source Caltrans 2020)

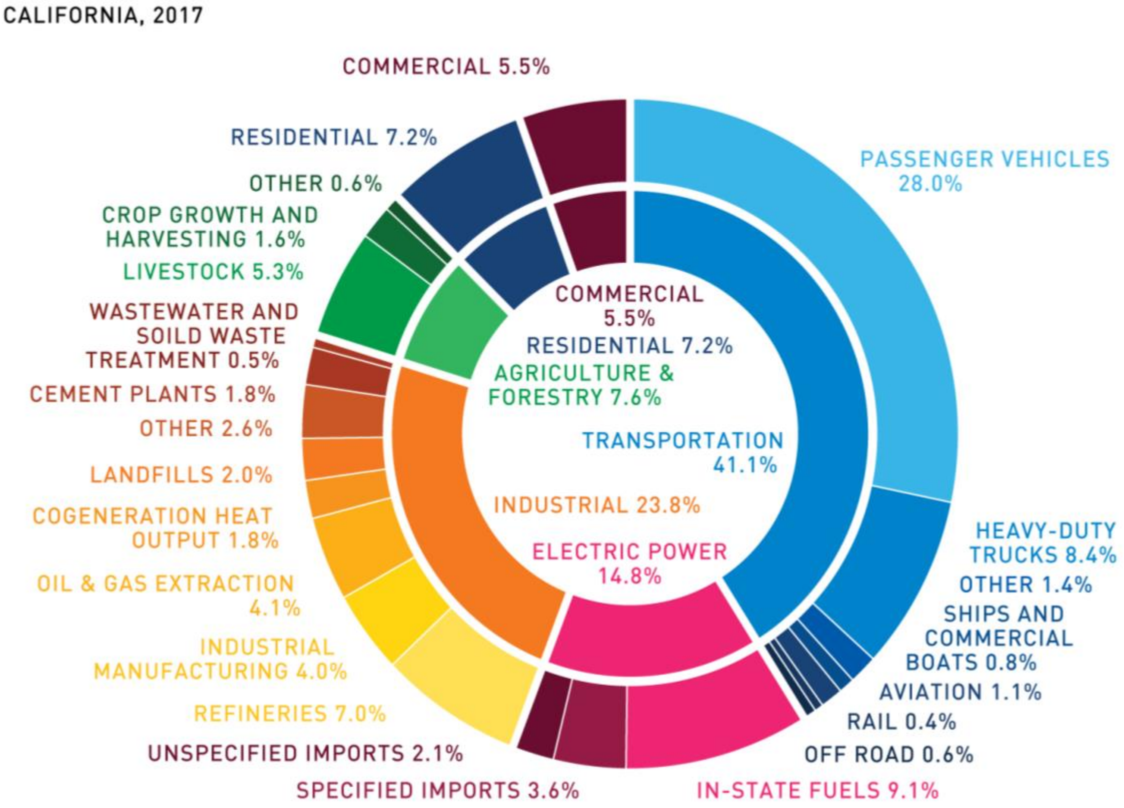
3 Current State of the Transportation System

3.1 Transportation, the economy, and greenhouse gas emissions

Transportation provides essential services, including access to jobs, health care, education, religious services, shopping, and much more. Affordable movement of goods through multiple modes is the lifeblood of the modern economy. Approximately 10% of U.S. Gross Domestic Product (GDP) is in transportation and transportation services, and no sector of the economy could exist in its current form without modern transportation. However, the current personal-vehicle-centric transportation system also contributes to many societal ills, including air pollution, climate change, road crashes, congestion, urban fragmentation, and unsustainable urban design, which are exacerbated for low-income and disadvantaged communities. Decades of vehicle-focused land use planning make cars a necessity for many communities and heavy-duty trucking as the primary method for goods movement and delivery, continuing the pattern of vehicle dependence. The overarching goal of sustainable transportation policy is to reduce these negative impacts while also improving transportation services and accessibility.

3.1.1 Energy use and emissions

The transportation sector is the largest emitter of GHGs in the United States, and is also a major source of local air pollutants. In California, transportation makes up 41% of GHG emissions, mostly from tailpipe emissions from cars and trucks (Figure 3.1). When the production and refining of oil is considered, transportation's contribution to GHG emissions rises above 50%.



NEXT 10 CALIFORNIA GREEN INNOVATION INDEX. Data Source: California Air Resources Board, California Greenhouse Gas Inventory – by Sector and Activity. NEXT 10 / SF · CA · USA

Figure 3.1. Greenhouse gas emissions by source (CARB 2018)

Unlike emissions from the power sector and from buildings, California's transportation emissions have not been falling over time (Figure 3.2). Some modest improvement in fuel economy and increased use of lower-carbon fuels has been generally outweighed by significant increases in driving.

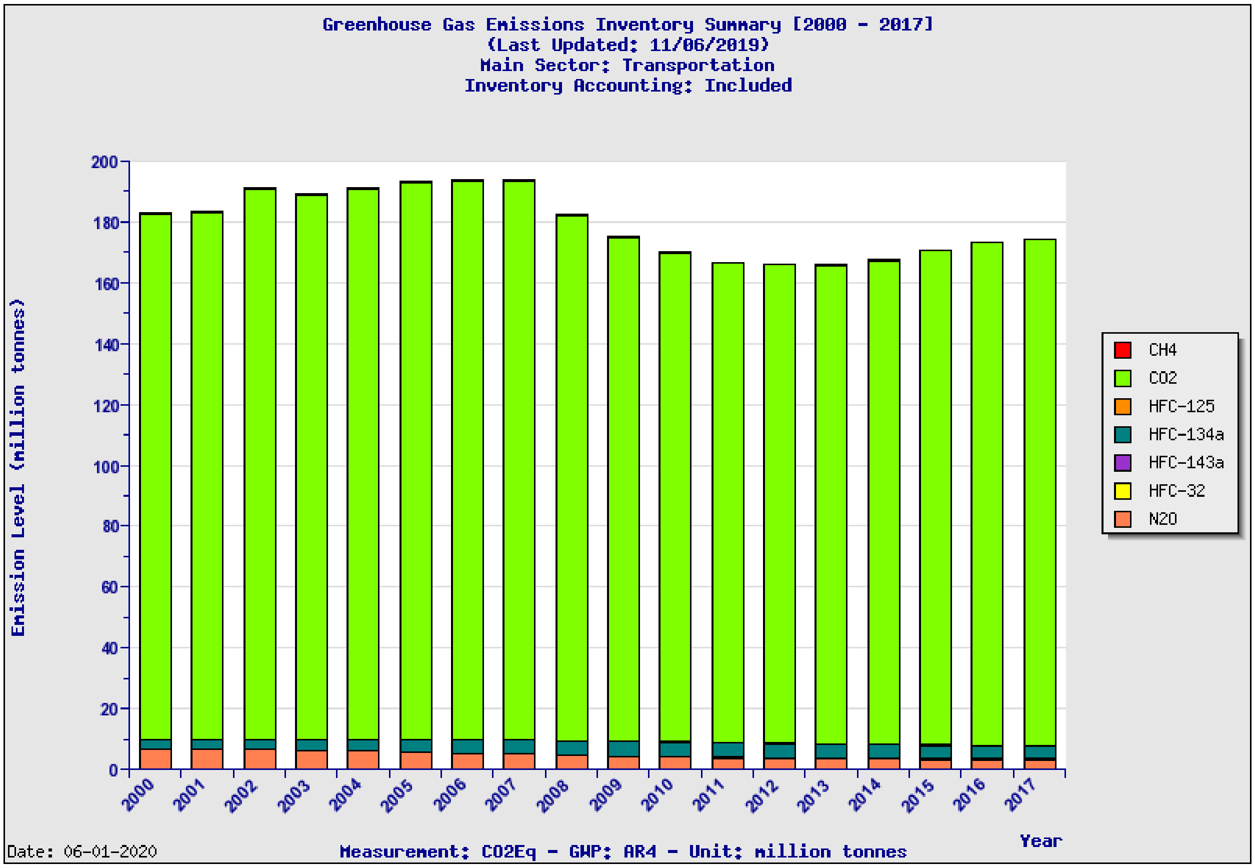


Figure 3.2. California Transportation Emissions over Time (CARB)

On-road vehicles, including LDVs (cars, sport utility vehicles [SUVs], etc.) as well as medium- and heavy-duty trucks, are responsible for the vast majority of transportation energy use and emissions in California (Figure 3.3). Aircraft and marine shipping emissions are significant, but often not included in state inventories. Other modes, including rail and transit, provide important transportation services but comprise a much smaller share of emissions.

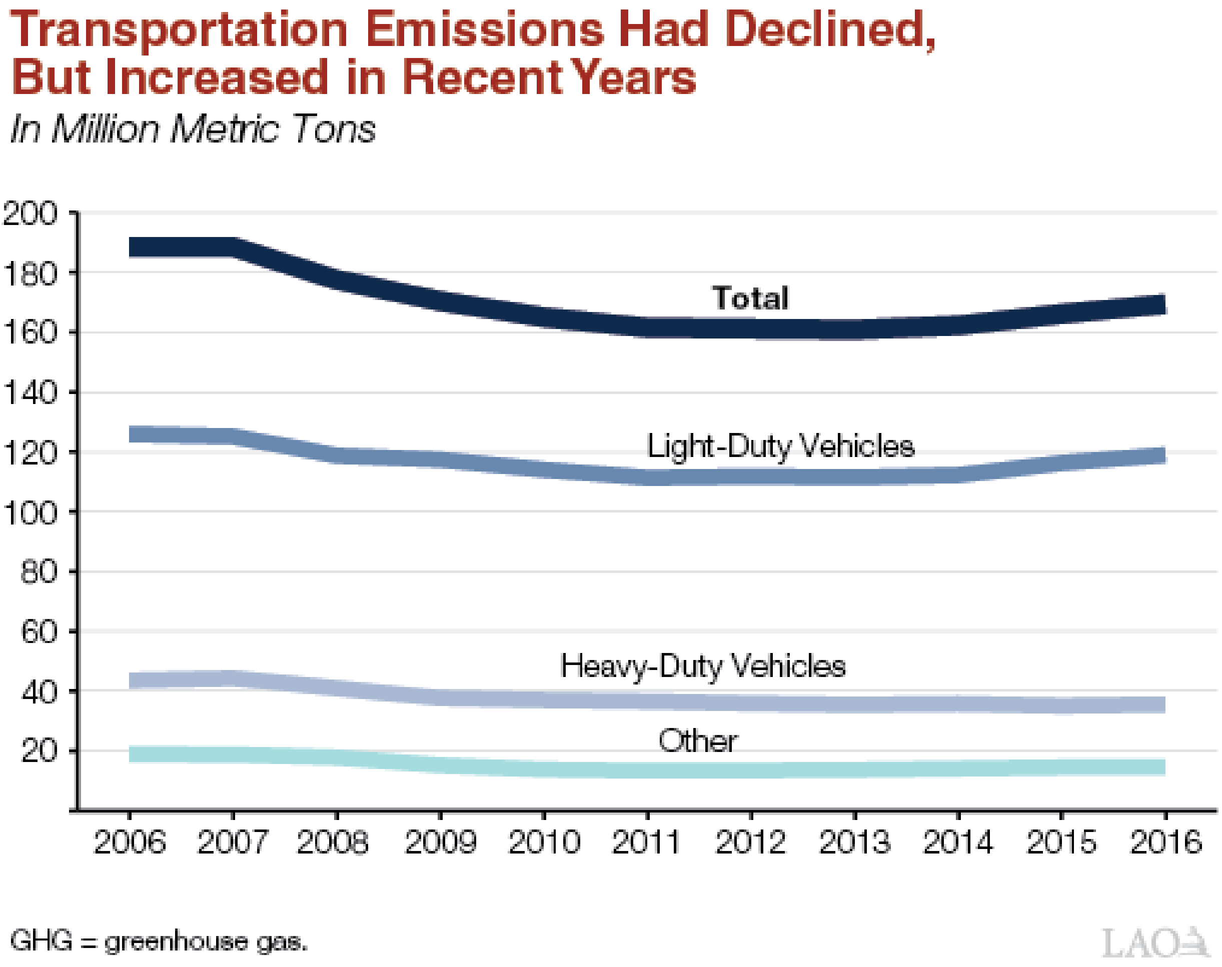


Figure 3.3. History of Emissions by Transportation Segment. Source: Legislative Analyst's Office based on GHG Inventory data.

The overall recent history of emissions is therefore one of modest progress in efficiency and significant early growth in electric vehicle deployment, as well as increasing use of biofuels, swamped out by an increase in demand for driving. The automobile and the truck have remained the most common way to travel and move goods respectively as mode shift to cleaner modes has been limited. The Great Recession significantly contributed to a net decline in emissions from 2008-2012, and it is difficult to disaggregate the effect of structural changes in efficiency or travel demand from the effects of the recession and recovery.

3.1.2 Infrastructure

Transportation relies on a large and expensive network of interconnected infrastructure. Physical infrastructure is required for every kind of transportation, including walking, cycling, driving (personal vehicle, ridehailing, carshare), transit, freight, maritime, rail, air travel, off-road and agricultural. As discussed above, LDVs and passenger travel are responsible for most of California's GHG emissions from the transportation sector. LDVs and passenger travel also account for the largest sources for (through fuel taxes) and recipients of (for roads and highways) transportation-related funding from the state and federal government.

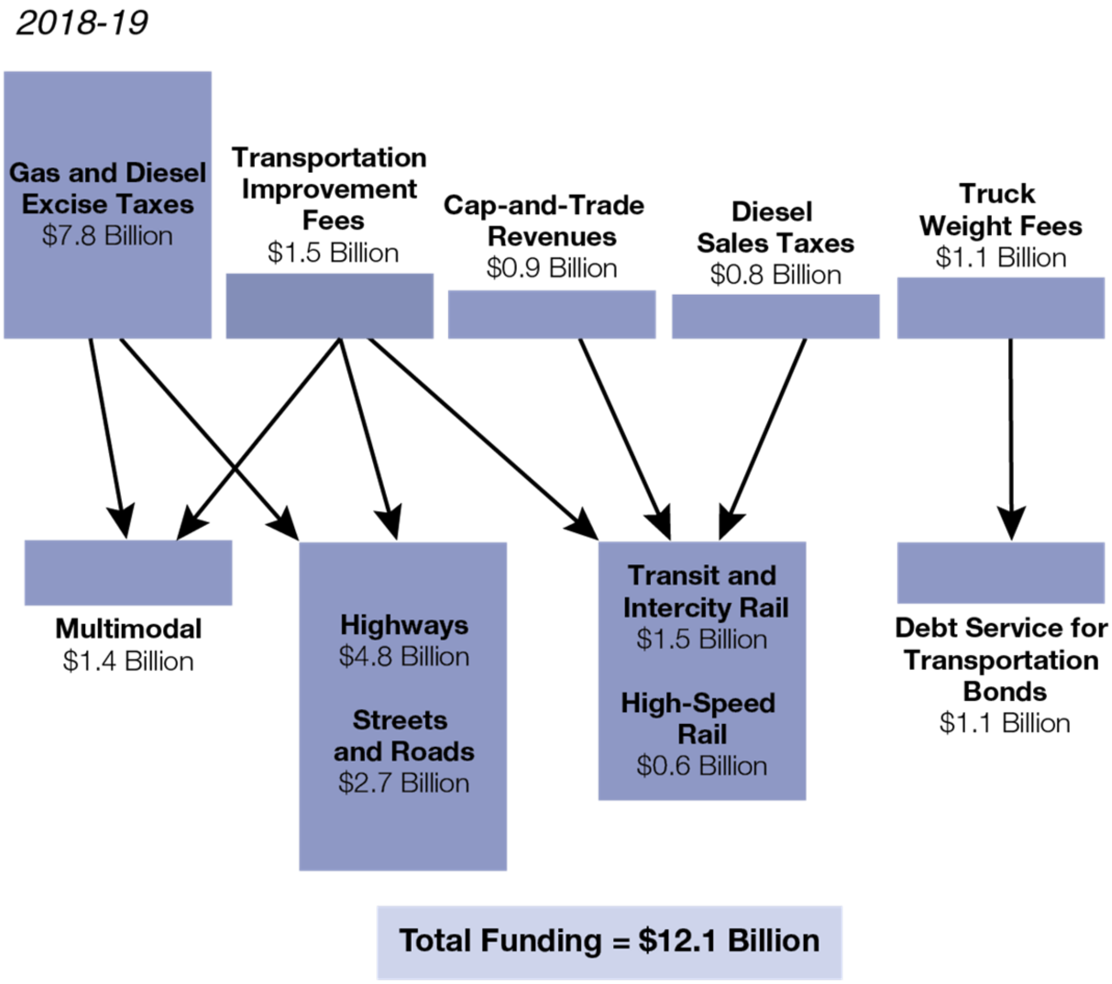


Figure 3.4. State Transportation Funding Flow. Figure adapted from Legislative Analyst's Office Report: California's Transportation System, page 46. (Legislative Analyst's Office 2018). Includes revenue from GGRF allocated for transportation. Multimodal includes multiple transit modes for one trip, such as bus and train.

Roads: California has 176,000 miles of public roadways, 59% of which are in urban areas [38]. Relatedly, most transportation expenditures in California include projects related to road construction, repair, and maintenance. Roadway expansion (adding more lane miles) accounted for 35% of transportation spending, which has been tied to an increase in VMT and GHG emissions through induced congestion [39]. An additional 35% of transportation spending was for road repair. Despite this, the condition of California roads has continued to worsen. Deteriorating road conditions has also been shown to increase in GHG emissions by reducing fuel economy and causing congestion and vehicle damage.

Freight rail: California has 4,800 miles of freight rail track owned, operated, and maintained by intermodal operators [40]. Freight rail is almost exclusively powered by diesel-electric locomotives, most of which are in line-haul, interstate operations and since 2007, consume Environmental Protection Agency (EPA) ultra-low sulfur (15 ppm) diesel fuel, per an agreement between the California Air Resources Board (CARB) and the two main interstate railroad companies operating in California, Union Pacific (UP) and Burlington Northern Santa Fe (BNSF). The 15 ppm sulfur standard was required for all interstate railroad operations in the U.S. in 2012. Where interstate trains refuel in California, they typically do so using CARB diesel, which maintains the same 15 ppm sulfur limit as EPA diesel, but has stricter limits on aromatic content and which typically reduces PM and NOx emissions compared to EPA diesel. Intrastate rail operations in California are required to operate on CARB diesel.

Transit and Passenger Rail: Unlike freight rail, passenger rail is a recipient of significant public funding. California has three heavy-rail systems for urban area passenger transit (Bay Area Rapid Transit [BART], part of Los Angeles Metro Rail, and Caltrain serving the communities between San Francisco and San Jose). There are also several regional and commuter rail systems, including Metrolink in the Los Angeles region, SMART in the Northern Bay Area, Coaster serving San Diego, and some Amtrak routes with enhanced commuter service. Los Angeles, San Francisco, San Jose, Sacramento, and San Diego also have light rail systems. The state's first high-speed rail network is currently under construction through the High-Speed Rail Authority (HSRA). 4% of the state's transportation program budget is allocated to transit and intercity rail, and 5% is allocated to high-speed rail. Passenger trains are operated on freight rail tracks, which are all owned by private entities, as well as publicly owned right of way. The National Railroad Passenger Corporation (NRPC), now Amtrak, was created by Congress in 1960 to oversee the operation of intercity passenger trains that utilize privately owned tracks. California's Public Transportation Account totaled $1.29 billion in 2018. Most of this account ($1.04 billion in 2018) is allocated to cities and counties to maintain public transportation infrastructure and service. Some passenger rail in California, e.g., BART, is electrified and draws either from the California grid or through a power purchase agreement (PPA) with specified sources of electricity. Other systems, e.g., Caltrain, are powered by diesel-electric locomotives, burning CARB diesel, though there are efforts underway to switch to electrify the train corridor.

Bus service usually uses the same road infrastructure as cars and trucks. A new exception is bus rapid transit, which include new infrastructure such as dedicated lanes, stations where fare is paid off-board, and platform-level boarding. Los Angeles, San Diego, and several other regions have bus systems with some of these elements. Of these, only Los Angeles' system has been scored by the Institute for Transportation & Development Policy, which rates the systems as Bronze (meaning it has many but not all of the preferred elements).

Ports: California is home to eleven commercial maritime ports, and is the largest port network in the country. The three largest ports in California are Los Angeles, Long Beach, and Oakland. Ports are used for international trade of agricultural and other products, but are also used for passenger services, tourist attractions, and other retail [41]. Some ports have begun to electrify their ship fleets and ground transportation, a transition that requires installation of new electrical and charging infrastructure for all sources, including vessels, locomotives, trucks, and passenger vehicles [42].

Airports: Airports require a huge variety of infrastructure for ground transportation, baggage, shelter, retail, security, air traffic control, and fueling. The federal government provides $14 billion per year on average to U.S.

airports for infrastructure projects, mostly through the Federal Aviation Administration's grant programs. The federal government also collects revenue from passenger fees and retail generated revenue [43]. Most major airports in California are seeking to electrify airside ground-support equipment. California has 26 major commercial passenger airports as well as many private airports, and airports used in agricultural regions that are not publicly funded [44].

Petroleum: California's oil and gas industry has been a central part of its economy for over 150 years, though production and its economic importance has been declining steadily (study 2 explores this in more detail). California has developed a large refining industry in parallel with its oil extraction activities. California has two major refining centers, in and around the cities of Los Angeles and San Francisco, with a statewide aggregate capacity around 1.9 million barrels of oil per day. California's petroleum market is somewhat isolated from that of the rest of the United States. While California imports 57% of its crude oil from foreign sources (primarily Saudi Arabia, Ecuador, Iraq, and Colombia) and a further 12% from Alaska [45], it imports very little finished fuel [46]. Pipeline connections to the rest of the continental United States are limited, with a few refined product pipelines distributing fuel from coastal refineries to markets in central California and Western Nevada. One significant pipeline connects the Los Angeles market with Phoenix, AZ. However, this pipeline generally conveys refined products from California Eastward rather than bringing products into the California market. The majority of petroleum trade through California occurs by ocean-going tanker or barge via petroleum terminals in San Francisco and Los Angeles.

Electricity: The electric grid has not traditionally been considered a component of transportation infrastructure, beyond some use of electricity for pipelines and commuter rail. As electric transportation becomes more widespread, the two sectors are becoming more linked. Relevant infrastructure includes generation, transmission, and especially the distribution and charging systems used to recharge electric vehicles. Electric utilities investment in charging infrastructure and grid upgrades to account for increased loads and demand management is critical for increasing the adoption of electric vehicles.

3.1.3 Transportation and the economy

Access to jobs requires high-quality safe, and accessible transportation services. In the many parts of the state where transit and cycling infrastructure is insufficient, this means owning a car, which creates equity issues. Indeed, access to a reliable vehicle is one of the strongest predictors of economic mobility for lower-income Californians [47]. Car access has ironically become especially important to Californians working in urban areas. Though it is generally easier to travel car-free within urban areas, very high housing costs and lack of multimodal infrastructure has made it impossible for many urban workers to have convenient and affordable access to jobs and other essential destinations by modes like walking, biking, and transit.

Movement of goods is also essential for the state economy. As of 2017, almost $1.5 trillion in shipments originated in California (over 10% of the value of total U.S. shipments) [47].

The rest of this section examines four key components of transportation in California. These are:

- Light-duty vehicles (LDVs): cars and light trucks (including pickups and SUVs). Most of these vehicles are personally owned and operated.

- Medium- and heavy-duty vehicles (MDVs and HDVs): generally defined as vehicles over 10,000 pounds, this subsector includes vehicles primarily used for the movement of goods.
- Vehicle miles traveled (VMT): the total miles travelled by all vehicles in the state, often used as a measure for demand. VMT is shaped by many factors and personal decisions, including land use, housing, mode choice, location of jobs and destinations, availability of biking and pedestrian infrastructure, and distribution of goods.
- Fuels: including all fuels that supply energy to transportation vehicles, such as gasoline, diesel, hydrogen and electricity.

3.2 Light-duty vehicles (LDVs)

3.2.1 Overview

With the introduction of a variety of new plug-in electric vehicles (PEVs)—including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—in the last decade, the market share of PEVs in California has been increasing annually. These vehicles, together with light-duty fuel cell electric vehicles (FCEVs), are commonly referred to in California as zero emission vehicles (ZEVs). The following section explores the state of ZEVs in California in 2020. The analysis synthesizes a large variety of data sources, including dealer association sale records, Department of Motor Vehicles (DMV) records, state agency records, and data collected by the UC Davis PH&EV Research Center. The analysis discusses vehicles as well as charging infrastructure, focusing mostly on the plug-in light-duty segment.

3.2.2 California's light-duty vehicle fleet

In 2018, according to the California DMV there were approximately 30 million LDVs in California. Gasoline-powered and other conventional-fuel vehicles still constitute 98% of the fleet (Figure 3.5). In order to reduce GHG emissions from the transportation sector and achieve carbon neutrality by 2045, the LDV fleet that is currently heavily dependent on fossil fuels needs to be almost entirely replaced by BEVs, PHEVs, and FCEVs, using very low to zero carbon electricity and fuels.

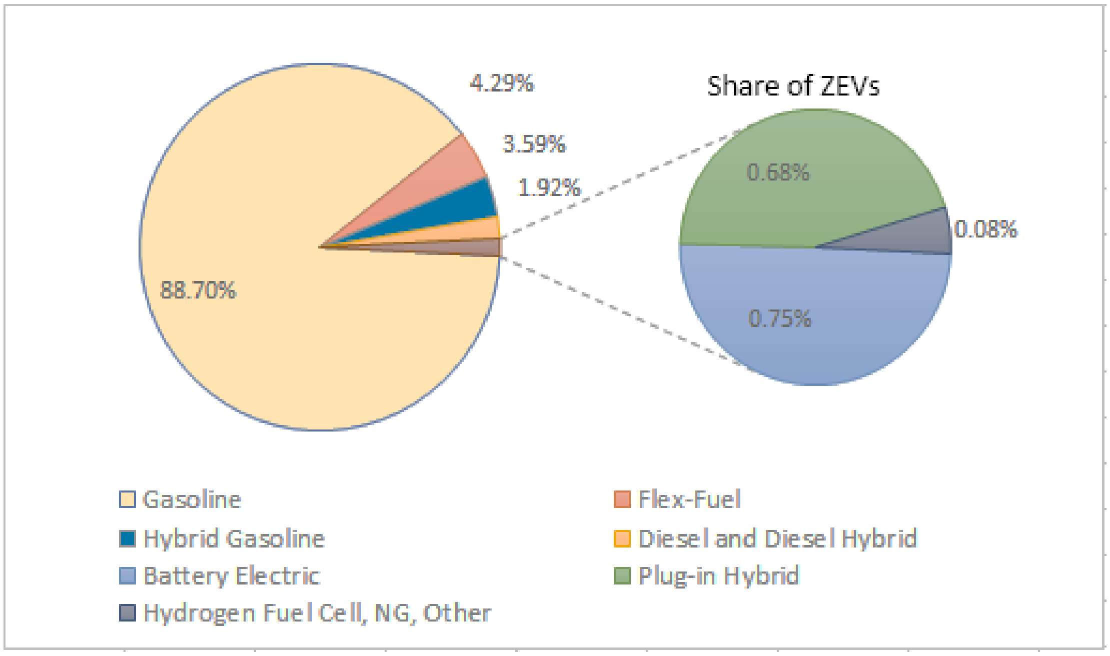


Figure 3.5. California LDV Fleet Composition (2018) by Fuel Type (CA Department of Motor Vehicles, published 2019)

Table 3.1. Total vehicle population by drivetrain type (2018)

Fuel Type	Count of Vehicles
Gasoline	26,685,840
Flex-Fuel[6]	1,290,066
Hybrid Gasoline	1,079,558
Diesel and Diesel Hybrid	577,819
Battery Electric	225,240
Plug-in Hybrid	204,002
Natural Gas	14,527
Hydrogen Fuel Cell	5,138
Other	4,926
Grand Total	30,087,116

The market share of BEVs and PHEVs (collectively known as PEVs) has been increasing over the past decade. Note that the share of hydrogen fuel cell vehicles (FCEVs) has been considerably lower than the share of BEVs

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[6] The classification follows from DataOne Vindecoder definitions of fuel type.

and PHEVs, largely due to price, limited supply and limited public fueling infrastructure, few available models, and low consumer interest so far. According to the California DMV and data reported by the California New Car Dealers Association, the share of PEVs in total new vehicle sales/registration went up from 3% in 2014 to 8% in 2019 (Figure 3.6). The share of PEVs in the total LDV stock of California increased from 0.4% in 2014 to 1.43% in 2018.

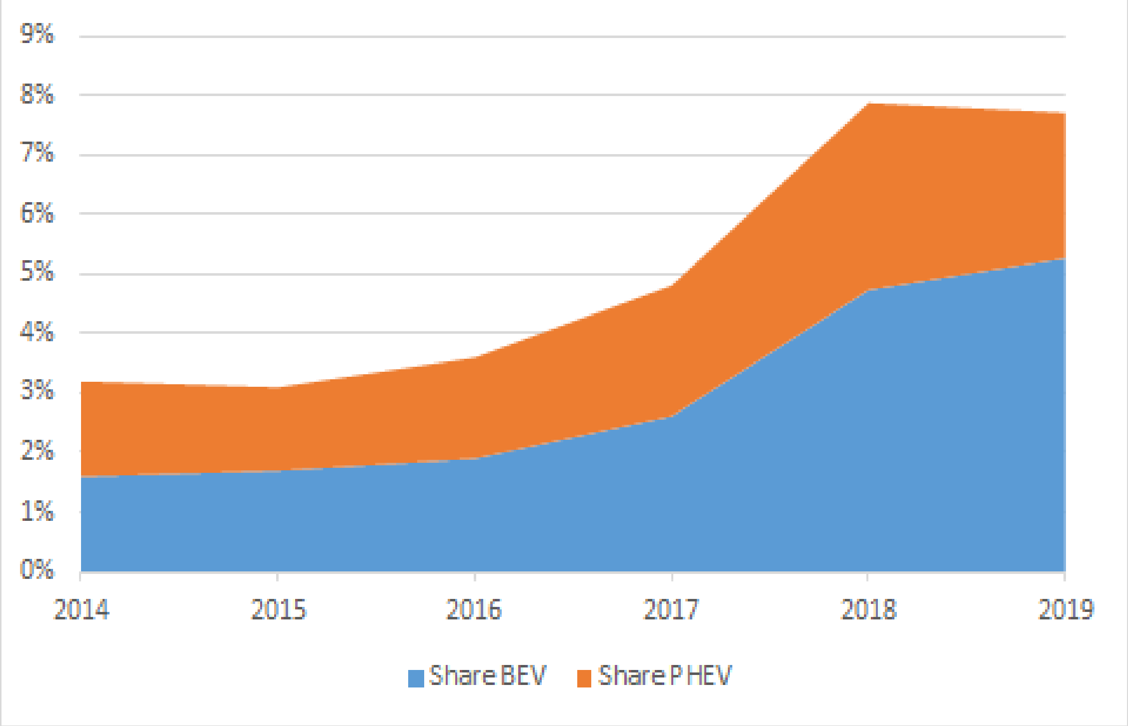

Figure 3.6. Share of BEVs and PHEVs in New Vehicle Registration (Source: California New Car Dealers Association)

The deployment of vehicles so far is not evenly distributed across income groups; areas with higher income populations and more total vehicles have a higher share of electric vehicles (Figure 3.7).

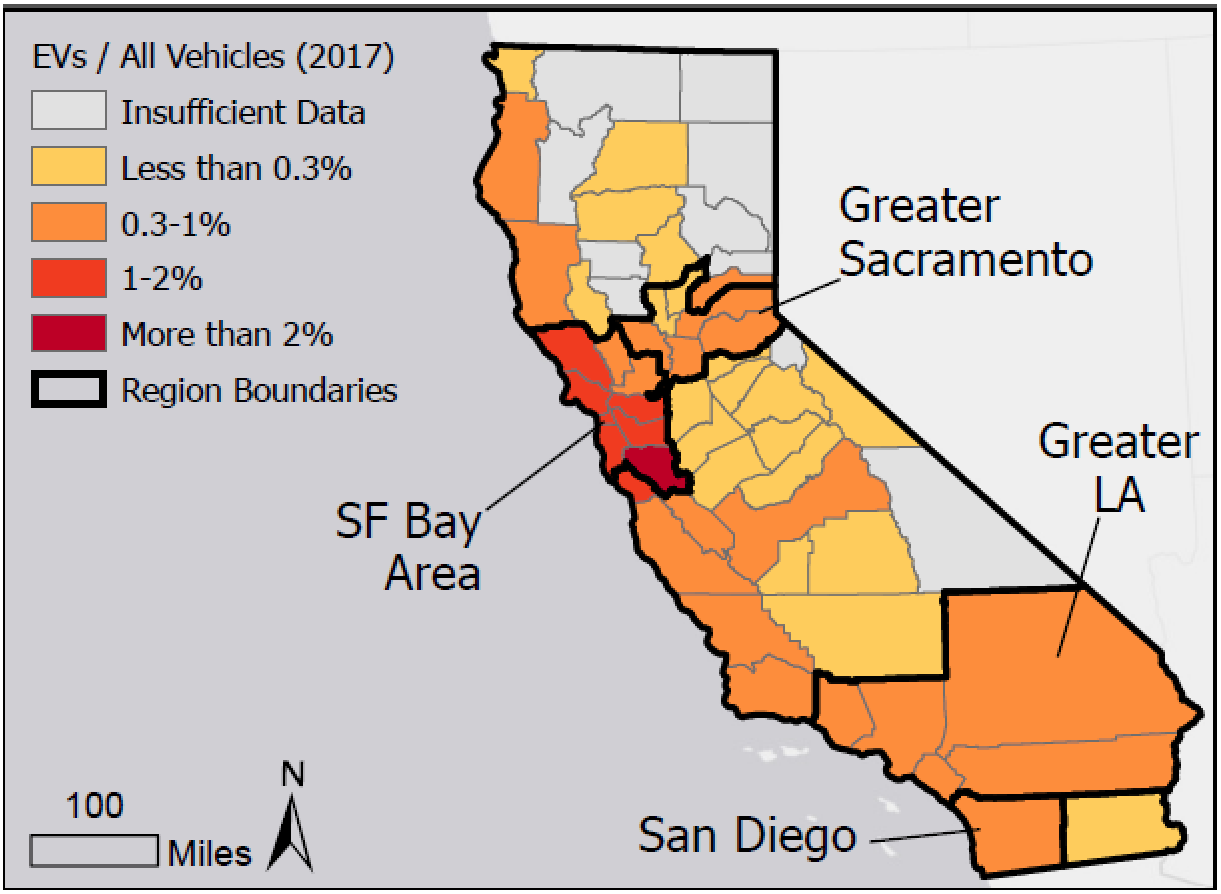

Figure 3.7. EVs as share of all vehicles

Over the years, federal and state governments, electric utilities, and a number of other stakeholders have provided support in the form of monetary and non-monetary incentives to accelerate EV purchases from qualifying manufacturers. For a limited number of first-time eligible EV buyers, rebates can go up to $7,000 towards the purchase or lease of a new PHEV, BEV, or FCEV, where the total includes increased rebate amounts for income-qualified applicants. It might be useful to note that CVRP rebates can be stacked incentives as well with qualifying PEV buyers receiving a rebate of $2000 under the Clean Vehicle Rebate Program (CVRP) for BEVs and $1000 for PHEVs. Past research has shown that every $1000 offered as a rebate or tax credit can increase average sales of PEVs by 2.6%. Incentive programs designed to encourage the adoption of PEVs have also been revised over the years to ensure equity through programs like the “Clean Cars 4 All” in California.

The share of BEVs compared to PHEVs has been increasing over the years (though as a caveat, this is based only on the vehicles receiving a vehicle rebate). In 2014, 56% of the CVRP applications were for BEVs and 43% were for PHEVs. In 2019, these numbers were 71% and 26%, respectively (Figure 3.8). One thing to note is that not all the BEV and PHEV models available in the market are eligible for the CVRP rebate. A PEV is not eligible for CVRP rebate if the base manufacturer suggested retail price (MSRP) of a PEV is more than $60,000, or the PHEV does not have at least 35 mile electric range, the eligible model is more than two years old, or the PEV does not meet the required tailpipe emission standards [48]. In general, though PHEVs have a major role to play as a transitional technology, it is necessary to have a higher share of BEVs with zero tailpipe emission in the LDV fleet to achieve carbon neutrality by 2045.

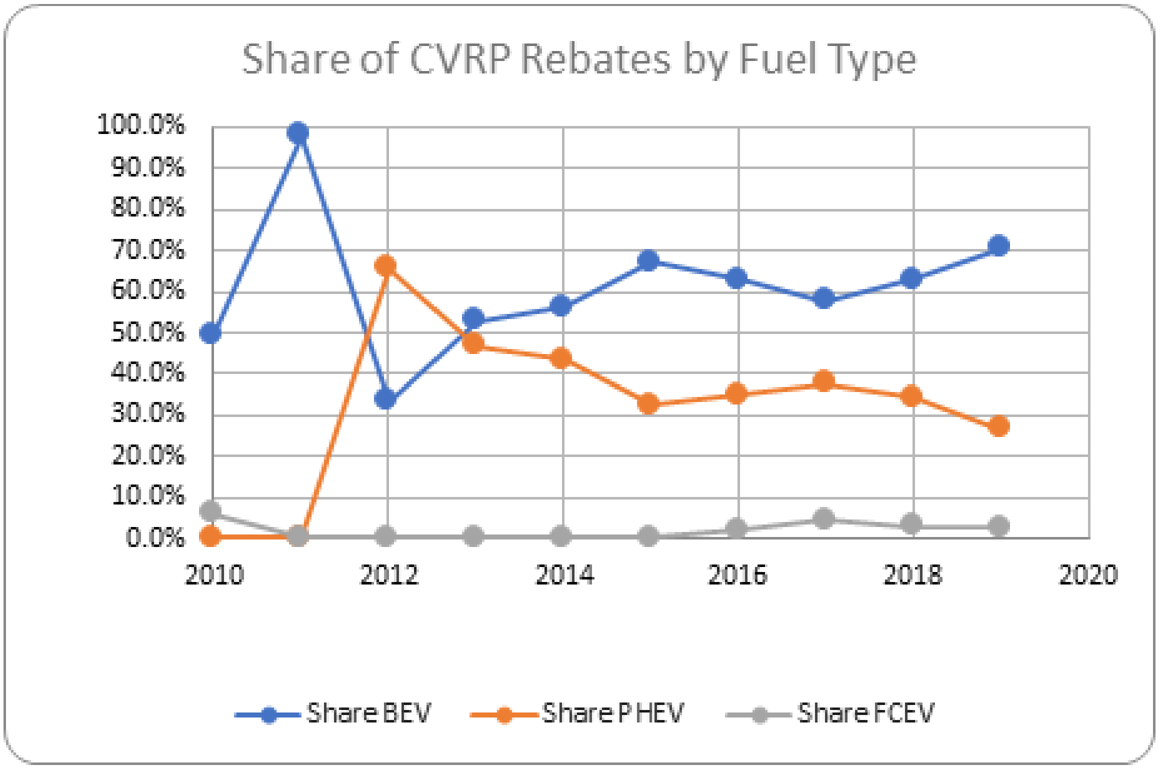

Figure 3.8. CVRP Applications by Fuel Type (2010-2019)[7]

When it comes to BEVs, a large share of the rebates in the past four years has gone to Tesla buyers while the share of Nissan Leaf rebates has dropped among first-time BEV adopters. In the case of PHEVs, adopters of the Chevrolet Volt, Toyota Prius Prime, and the PHEVs offered by Ford like the Fusion and the C-Max Energi have claimed the majority of CVRP rebates (Figure 3.9 and Figure 3.10)[8]. The shift from first generation BEVs such as the Nissan LEAF to longer range vehicles such as the Chevrolet Bolt and Tesla (Model S, Model 3, or Model X) and the higher share of longer range PHEVs in the LDV fleet may lead to a higher share of electric miles driven.

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[7] In 2011, the PHEV share of the CVRP rebates was zero even though the Chevrolet Volt was introduced concurrently with the Nissan LEAF because the former didn't meet the required super ultra-low emission vehicle tailpipe emission standards.

[8] The Ford Fusion and C-Max Energi are no longer eligible for the CVRP rebate.

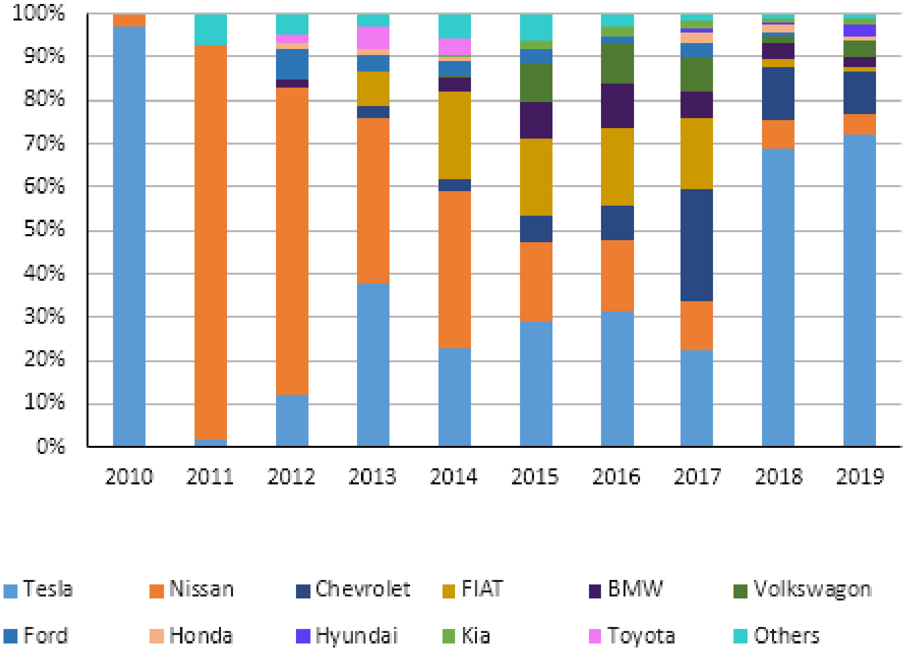

Figure 3.9. CVRP Applications by Vehicle Make (BEVs)

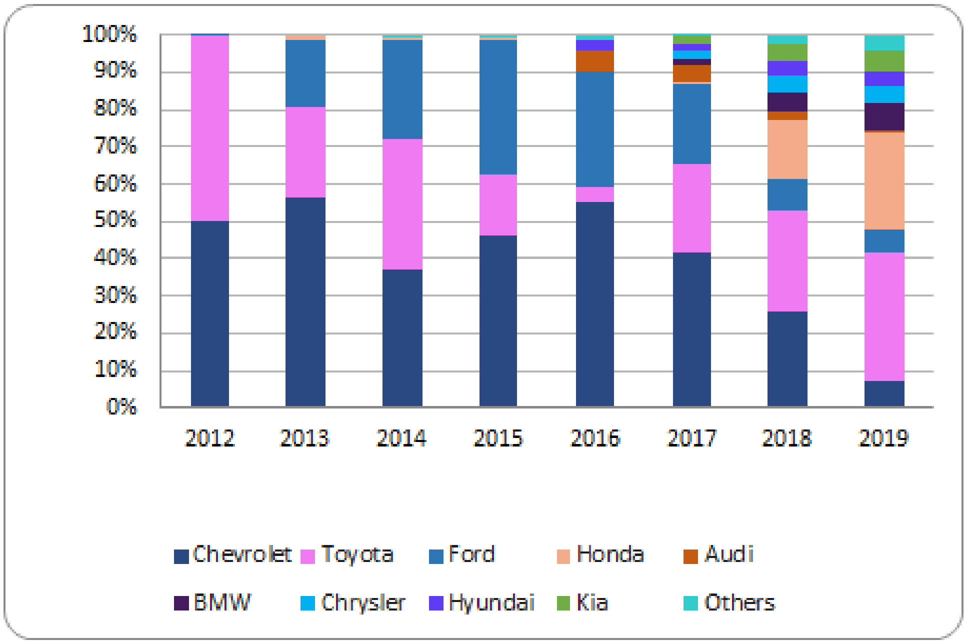

Figure 3.10. CVRP Applications by Vehicle Make (PHEVs)

In addition to the monetary and non-monetary incentives (e.g., High-Occupancy Vehicle (HOV) lane access) offered to PEV adopters, household socio demographics, access to charging infrastructure, and vehicle-buyer characteristics (e.g., environmental attitudes and social networks) play an important role in the decision to adopt PEVs. The impact of incentives is also heavily impact by the public awareness of the PEV and incentives availability and by the supply of those vehicles [49].

One of the major barriers in PEV adoption is the high purchase price of these vehicles in comparison to a gasoline-powered vehicle in the same vehicle segment. In this scenario, used PEVs with a lower purchase price can play an important role in increasing the market penetration of PEVs. Though the market for used PEVs is still nascent, the numbers have been going up in the past few years. According to the California DMV vehicle registration data, between 2016 and 2017, the sales of used BEVs went up by 30%.[9] Considering both BEVs and PHEVs, the market for used PEVs increased by 15% (Figure 3.11). One can hypothesize that the recent increase in the number of PEV transactions in the secondary market is influenced by leased vehicles that have been returned after the lease period.

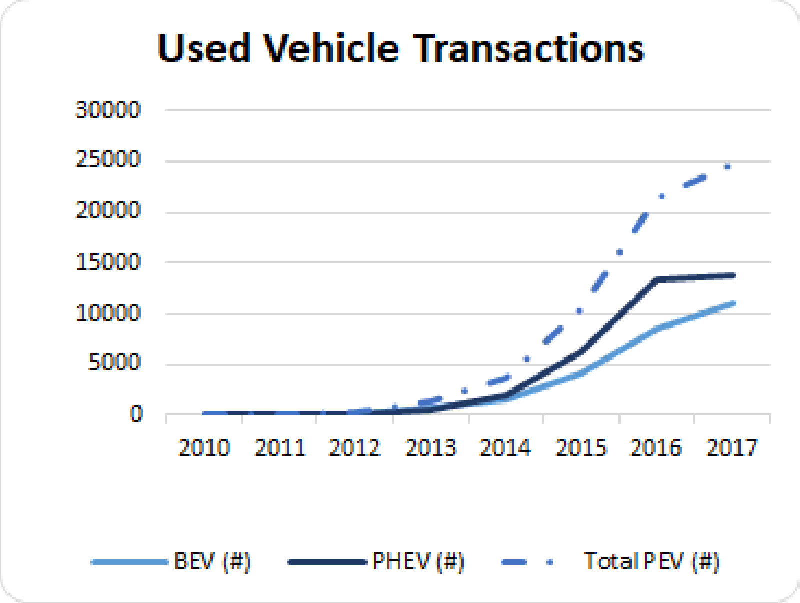

Figure 3.11. Used PEV transactions in California

In terms of spatial distribution, California DMV data indicates that distributions of the used PEV market is similar to the distribution of new PEV sales. In other words, factors mentioned above (like social network or neighborhood effect and access to charging infrastructure) that influence an individual's exposure to new technology also play an important role in the used PEV market. However, the market for used PEVs is less concentrated than for new PEVs. Analysis of the distribution of new and used PEVs was performed using the Lorenz curve and Gini coefficients, two standard economic measures of inequality. The Lorenz curve in Figure 3.12 shows the cumulative proportion of the California's PEVs on the vertical axis, with the cumulative proportion of all vehicles on the horizontal axis, and the Gini coefficient measures the area between the curves and the diagonal line labeled "equal distribution." If PEVs were evenly distributed throughout the state, the curves would follow the diagonal line, and the Gini coefficient would be 0. If PEVs were completely concentrated in a single area, the curve would be almost flat at 0% on the vertical axis, and the Gini coefficient would be 1. Analysis of the distribution of new and used PEVs in California as a proportion of all vehicles shows that while all

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[9] Only tracking in-state transactions. The DMV data does not allow us to identify whether an older vehicle (older model year) originally registered out of state is a used vehicle transaction or whether the household moved to California from a different state. We do not have access to DMV data for 2018 or later years.

electric vehicles are densely concentrated in a small number of zip codes in particularly dense areas, used PEVs are somewhat less concentrated than new PEVs (Figure 3.12). The Lorenz curve for used vehicles is closer to the line of equality than the curve for new vehicles, and the Gini coefficient for used vehicles (0.422) is somewhat lower (0.566). This suggests that used PEVs are playing a role in expanding access to electric vehicles into new areas.

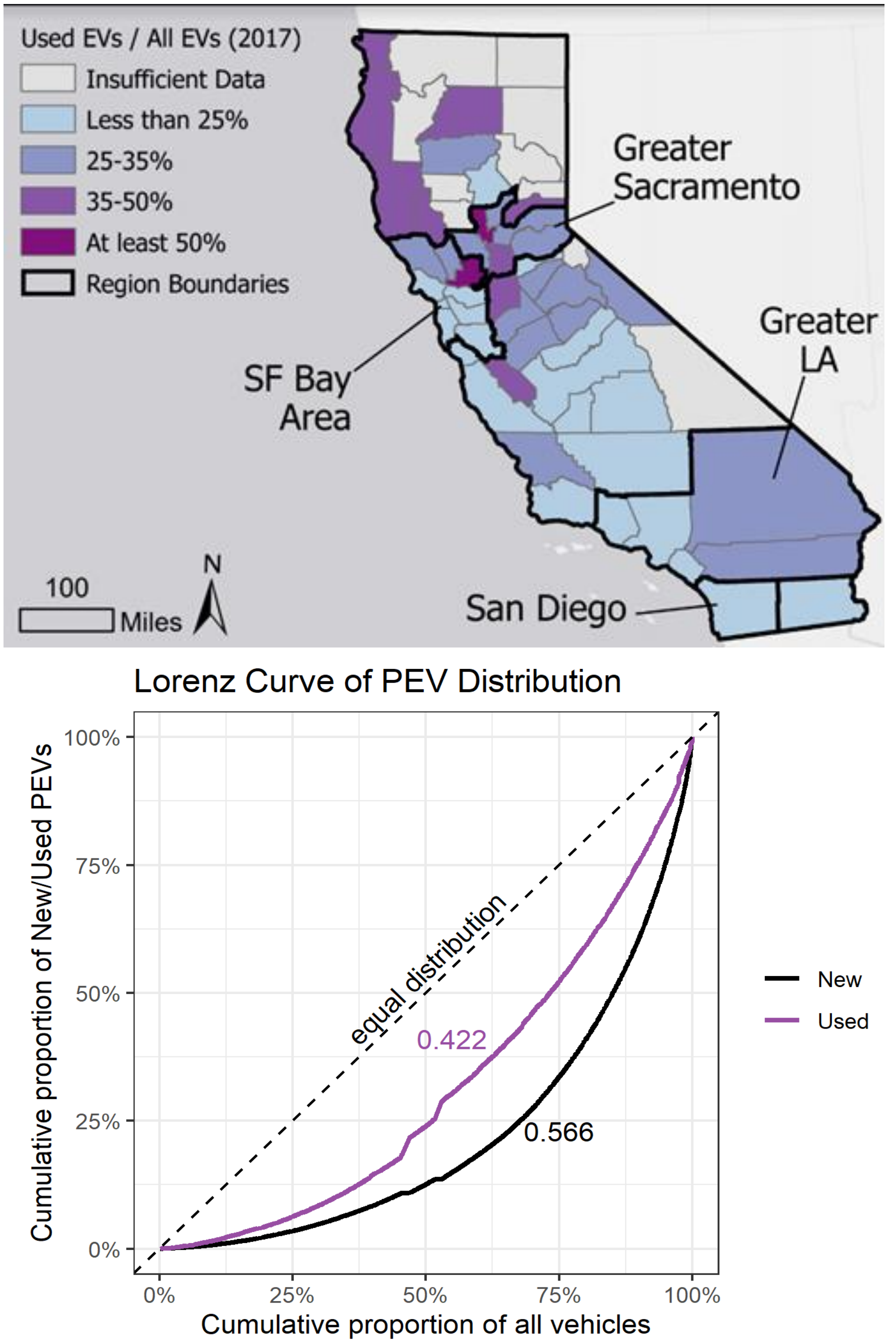


Figure 3.12. Spatial and Lorenz Distribution of Used and New PEVs in California

3.2.2.1 Vehicle Charging Infrastructure

Though a variety of alternative-fuel vehicles have been developed over the last decade, plug in-electric vehicles are being adopted most rapidly as an alternative to internal combustion engine (ICE) vehicles. In contrast to ICE vehicles, PEVs can be refueled (charged) anywhere if an electrical outlet is available. Currently, three types of chargers are commonly used by PEV drivers in the U.S.—Level 1 (L1), Level 2 (L2), and DC fast—each of which have different charging powers.

Charging an electric car can be as simple as plugging in your phone into home power. Almost 80% of the light duty vehicles in California used by detached houses dwellers and are more likely to be able to charge at home. For multi-unit dwellings overnight charging will require public infrastructure installations [50]. Charging can also be similar to refueling a gasoline car, where you start by using your credit card and then plugging in a large nozzle. Figure 3.13 summarizes different charging types.

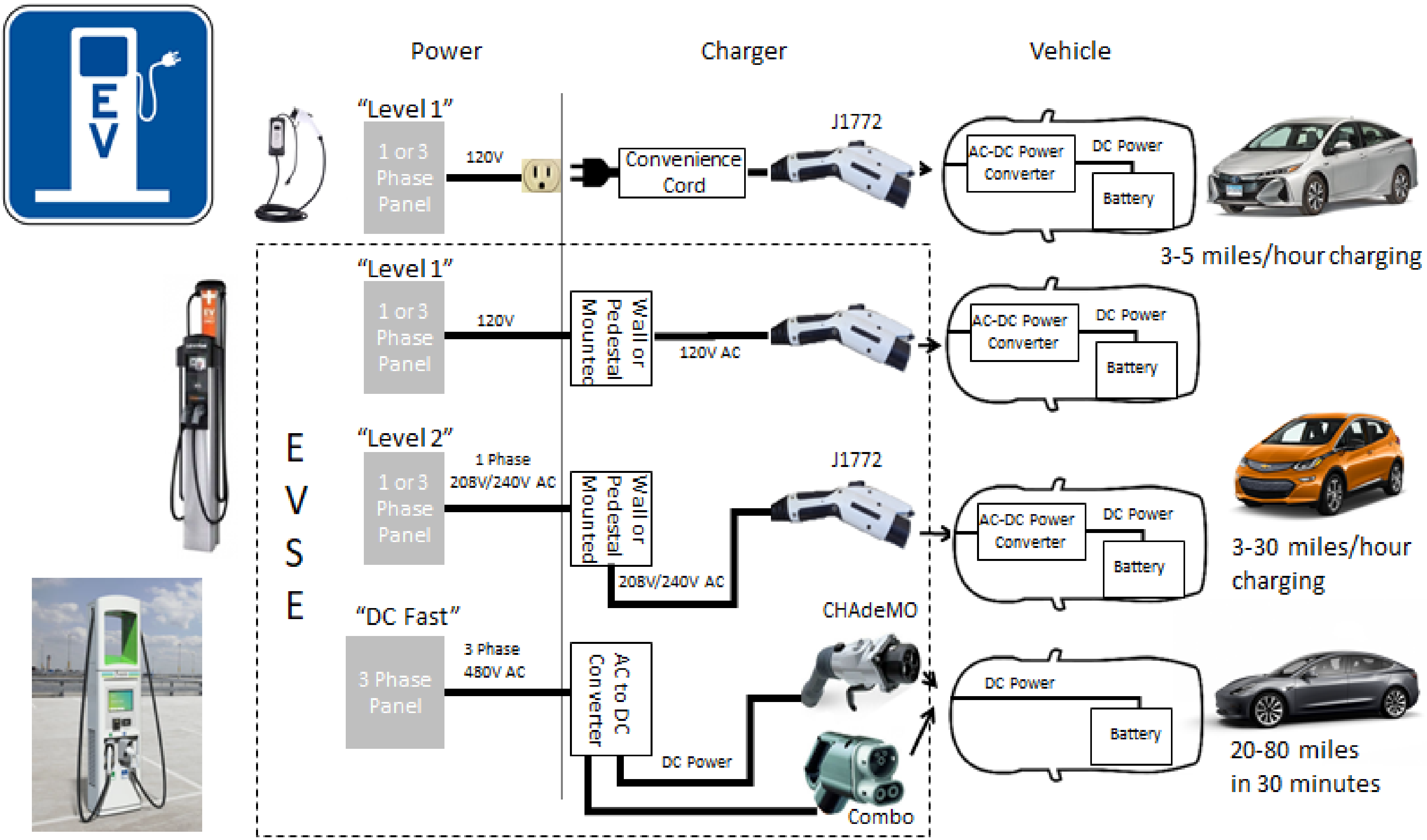


Figure 3.13. Charging options at Home and Electric Vehicle Supply Equipment (EVSE) Types

According to the UC Davis PH&EV Center survey that include a 7 days charging diary [51]. Home charging is the most common choice for PEVs. In many cases home charging relies on L1 convenience cords charging, thereby circumventing the need to install additional charging infrastructure. For longer daily trips or larger battery L2 EVSE chargers are more common (Figure 3.14).

Charging while at work at designated workplace charging or at a public charger are the second-most common charging options, after home charging. Together, home and work charging cover more than 80% of total charging events. To estimate the number of chargers available in California, we combined data from two publicly available sources (Plugshare [52] and the alternative Fueling Station Locator [53]), removing duplicated locations that appear in both datasets and compare this against data from the PH&EV Center surveys on workplace charging locations of more than 15,000 PEV users in California (Table 3.2).

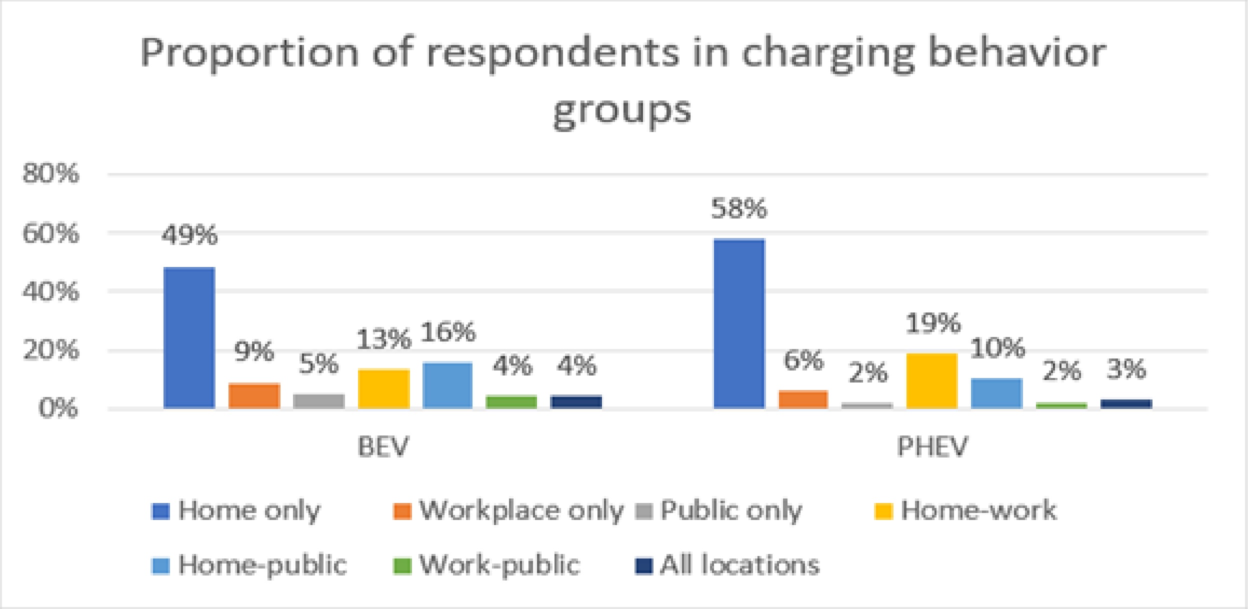


Figure 3.14. Charging Behavior of BEV and PHEV Users Who Responded to the Initial Survey (N=7,979)

Table 3.2. Number of chargers California 2020

Region	Workplace Chargers at least:	Public Level 2	Public DCFC
Greater Sacramento	600	1,600	500
San Francisco Bay Area	15,500	9,500	2,300
Greater Los Angeles	17,400	12,100	2,700
San Diego	2,300	2,200	500
Rest of California	1,600	2,800	1,400
Statewide Totals	37,600	28,200	7,400

The total number of workplace chargers available for commuters is higher than the total number of public chargers by more than 20%. Workplace chargers are more common in California's main metropolitan areas (Figure 3.15).

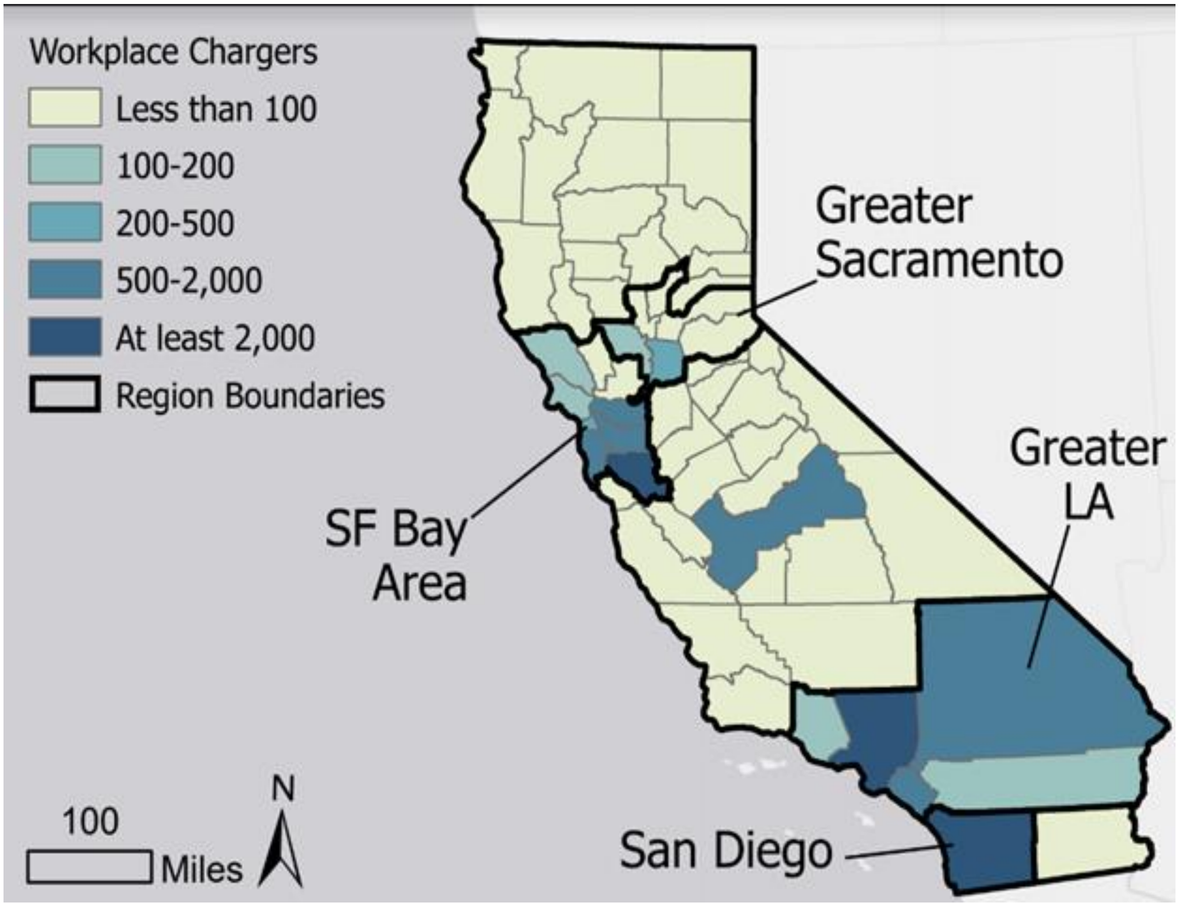


Figure 3.15. Fast charging distance from Home

DC fast chargers are mostly used for BEVs around home as a substitute for home and work charging, when more charging is needed and in a few cases for trips longer than the range of the vehicle.

A recent analysis by the PH&EV Center of about 200 vehicles over a year shows that most DC fast charger events happen within 40 miles from home. Only 7% of the Bolt (240 miles range) fast charging happens more than 100 miles from home and about 17% of the Tesla charging events happened on long trips away from home (Figure 3.16).

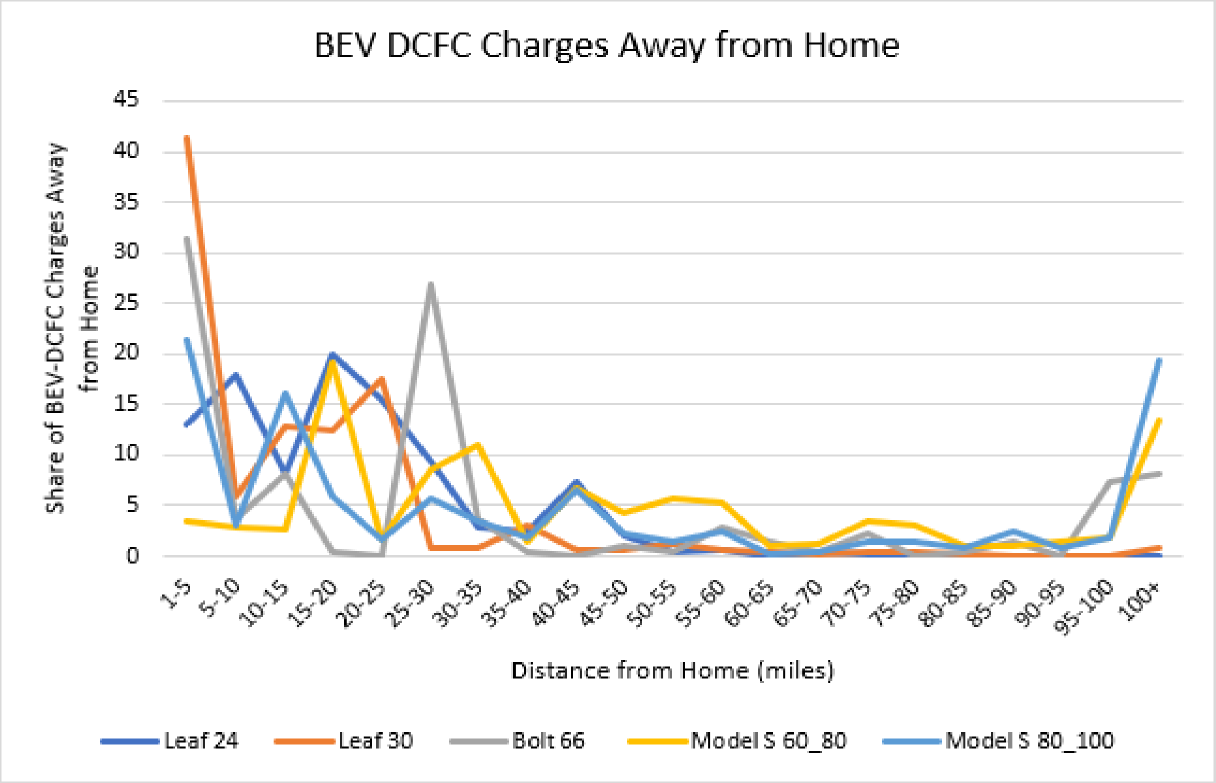
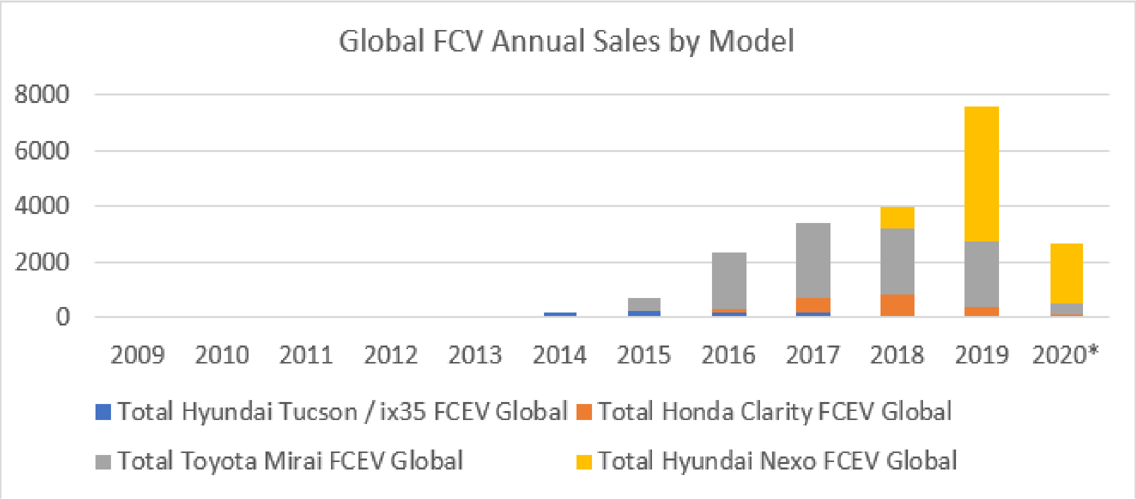


Figure 3.16. Fast charging frequency by distance from home

3.2.3 Fuel cell vehicles

Several automakers are promoting FCVs to consumers. These vehicles are often compared to BEVs. Both vehicle types have zero tailpipe emissions, can be fueled by renewable energy, and are driven by electric motors. Apart from purchase price, the key difference between these vehicles is their driving range and refueling style. When BEVs were first introduced into the market, most had driving ranges of 100 miles, though BEVs with almost 400 miles of range are now available. FCVs have driving ranges of more than 300 miles (and may be longer with larger hydrogen tanks) and can be refueled in less than 10 min at a hydrogen fueling station. Unlike PEVs, FCVs are still in earlier phase with very low volumes of production and in most cases lease only agreement that include free hydrogen. The following section explores the global market in which California is the largest player, though other markets such as South Korea will likely overtake the CA market in 2020 Our data does not separate between the USA and California market but because of lack of publicly available refueling infrastructure outside of California we assume that all privately used FCVs sold in the US are in California. Three original equipment manufacturers (OEMs) currently offer FCVs in California, with the Toyota Mirai being the most common (Figure 3.17). Sales of these vehicles began in 2014, with most vehicles leased for a period of three years. OEMs generally subsidize hydrogen fuel cost, which would otherwise be much higher than for PEVs and internal combustion engine vehicles (ICEVs).



Note: Sales data does not include limited production vehicles.

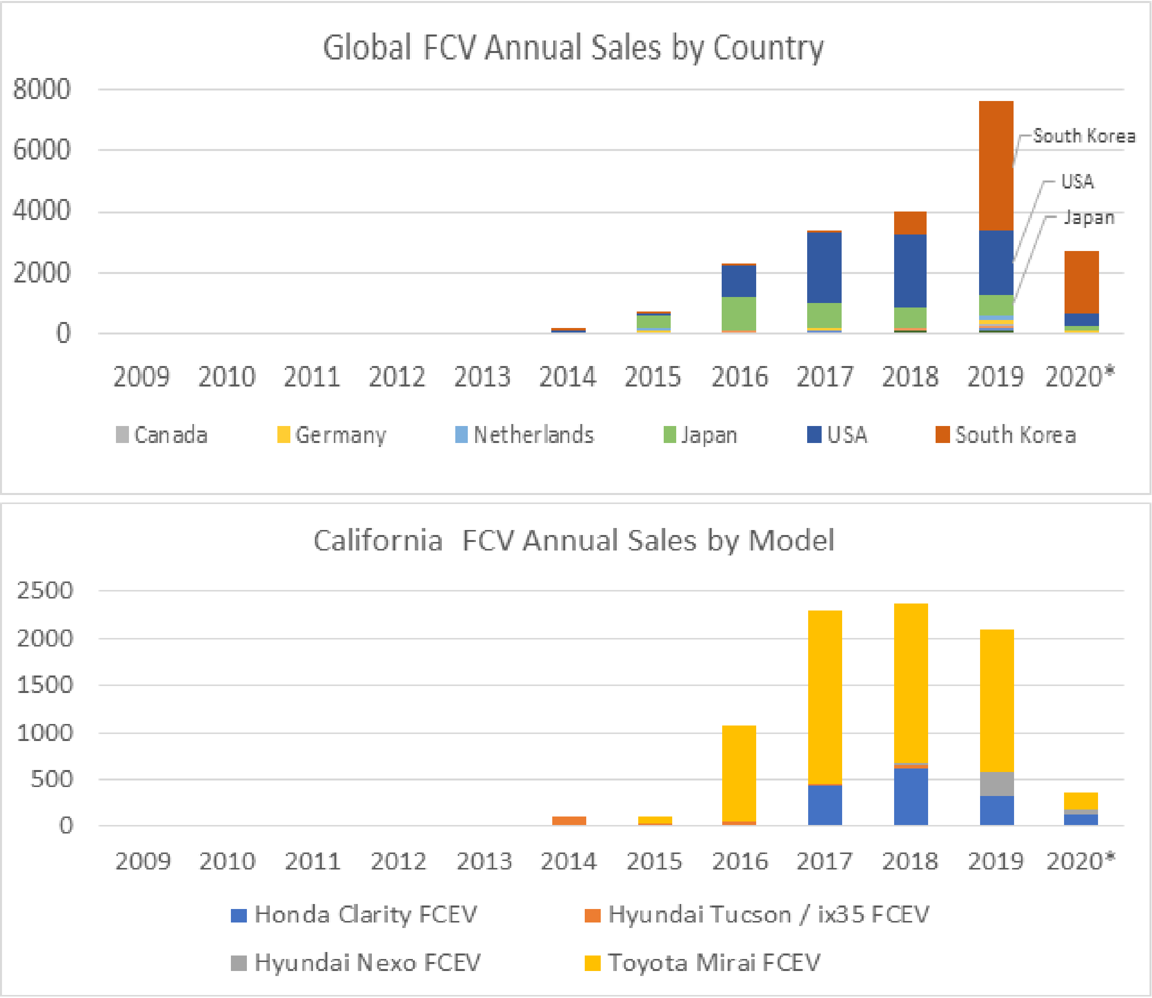


Figure 3.17. Fuel Cell Vehicle Sales by Model, Country, and Model for California

As of 2020 California currently has 43 active hydrogen-fueling stations, built through a combination of industry funds and capital and operating cost support from the California Energy Commission (CEC). These are predominantly located in the Los Angeles, San Francisco Bay, and Sacramento and Bay areas as shown in Figure 3.18, below.

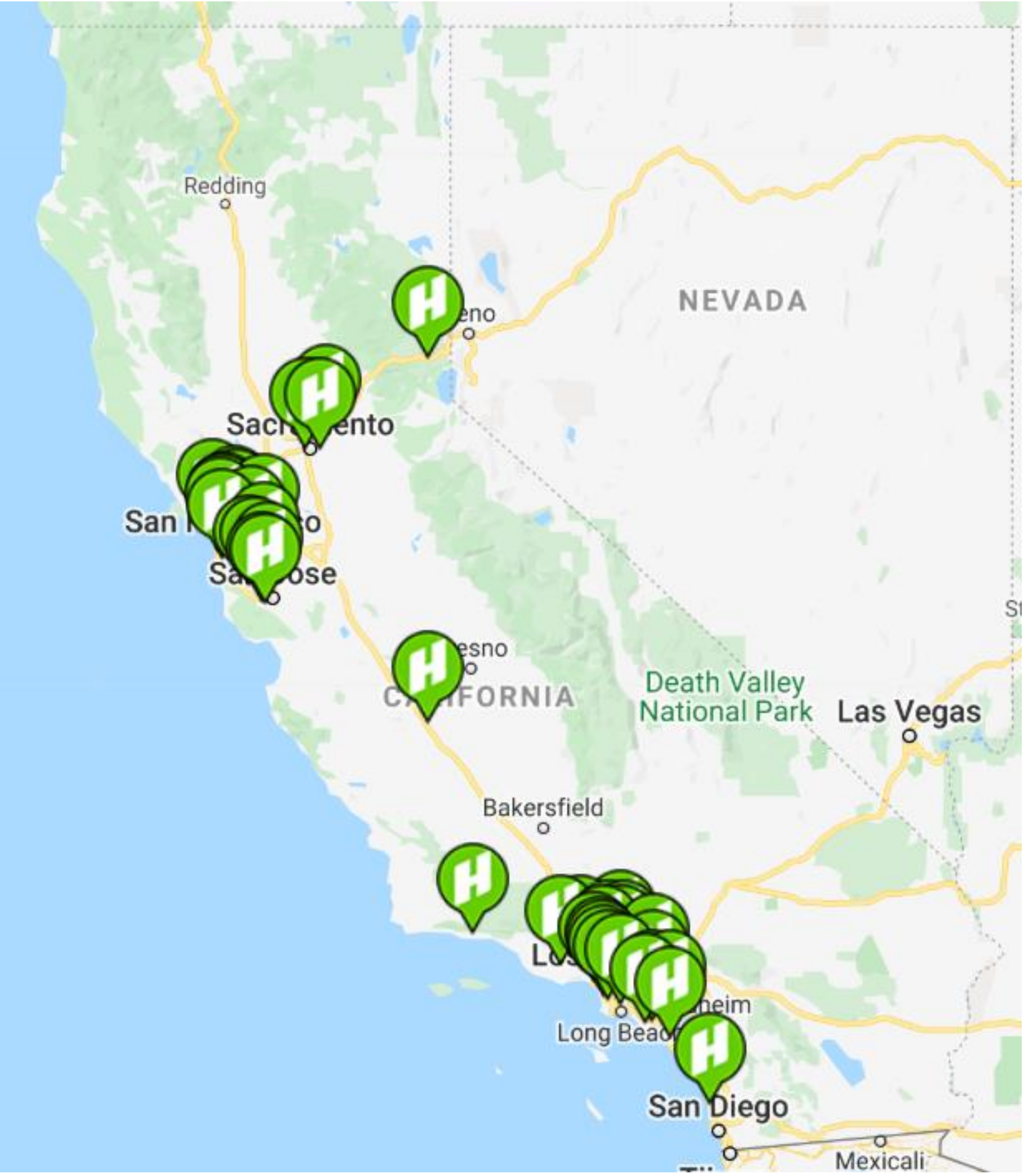


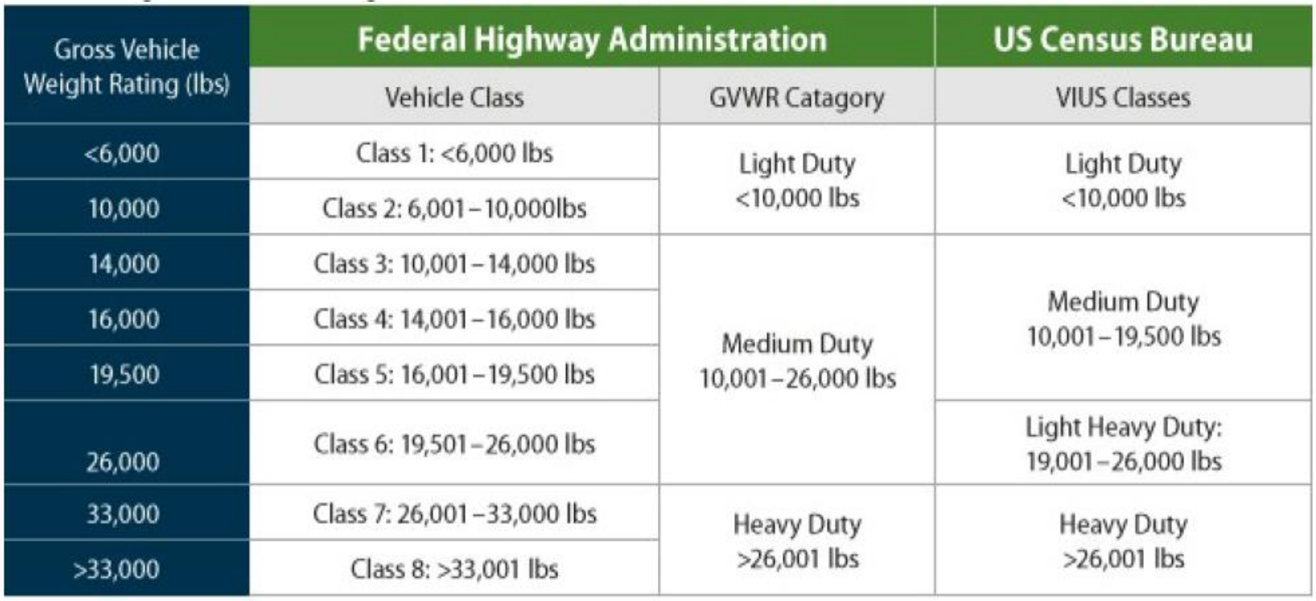
Figure 3.18. California Active Hydrogen Station Map. Source: https://cafcp.org/stationmap

3.3 Heavy-duty vehicles (HDVs)

3.3.1 Total number of HDVs

To characterize HDVs, we relied on the widely used eight vehicle classes defined by the Federal Highway Administration (FHWA) and the U.S. EPA. These classes are based on gross vehicle weight rating (GVWR), which represents the maximum weight of a vehicle (vehicle weight + fuel + passenger weight + cargo weight) as specified by its manufacturer. Table 3.3 summarizes FHWA weight classes and categories.

Table 3.3. FHWA weight classes (Source AFDC [54])



Gross Vehicle Weight Rating (lbs)	Federal Highway Administration		US Census Bureau
	Vehicle Class	GVWR Catagory	VIUS Classes
<6,000	Class 1: <6,000 lbs	Light Duty <10,000 lbs	Light Duty <10,000 lbs
10,000	Class 2: 6,001–10,000lbs		
14,000	Class 3: 10,001–14,000 lbs	Medium Duty 10,001–26,000 lbs	Medium Duty 10,001–19,500 lbs
16,000	Class 4: 14,001–16,000 lbs		
19,500	Class 5: 16,001–19,500 lbs		
26,000	Class 6: 19,501–26,000 lbs		Light Heavy Duty: 19,001–26,000 lbs
33,000	Class 7: 26,001–33,000 lbs	Heavy Duty >26,001 lbs	Heavy Duty >26,001 lbs
>33,000	Class 8: >33,001 lbs		

Figure 3.19 displays the number of trucks in California for selected categories. Between 2011 and 2020, there was a steady increase in the number of long-haul (more than 200 miles from origin to destination) (+40.5%), short-haul (+58.1%), and heavy-duty vocational trucks (+37.5%). The number of heavy-duty pickups and vans also increased, but only by 10.5% (not shown because the number of heavy-duty pickups and vans is much higher than for other categories of trucks in California). This growth was partly due to the expansion of the logistics industry (~+67% in revenue for the US between 2010 and 2018; see [55]), the development of online shopping, and to a lesser extent to population growth in California (+7.2% between 2010 and 2019; see [56].

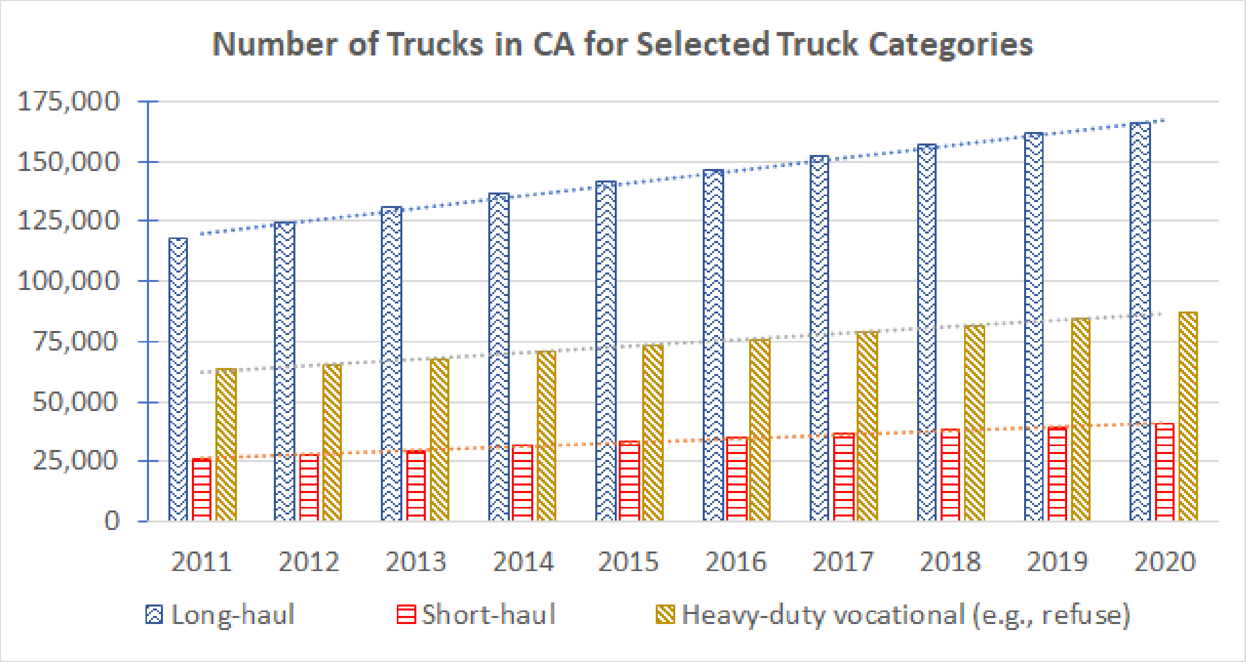


Figure 3.19. Number of California trucks in selected categories

3.3.2 Duty cycles and types of trucks

Currently, approximately 98% of Class 8 HDVs are powered by diesel ICEs, and the balance by natural gas (NG) engines [57].

Whereas LDVs typically serve to transport drivers, passengers, and occasionally small amounts of cargo from one location to another, HDVs tend to be specialized in sets of tasks, such as hauling goods over long distances, transporting containers from ports to distribution centers or railyards, transporting sand or gravel to cement plants, or collecting refuse from households and bringing it to landfills. This specialization decreases economies of scale attainable with LDVs and increases the cost of transitioning to alternative fuels.

Figure 3.20 gives a picture of the change in the number of alternative-fuel trucks in California (based on EMission FACtor [EMFAC] 2017 [57]). A comparison with Figure 3.19 confirms that alternative fuel trucks are still only a very small percentage of trucks in California, although their numbers are growing (especially for hybrid and compressed NG trucks).

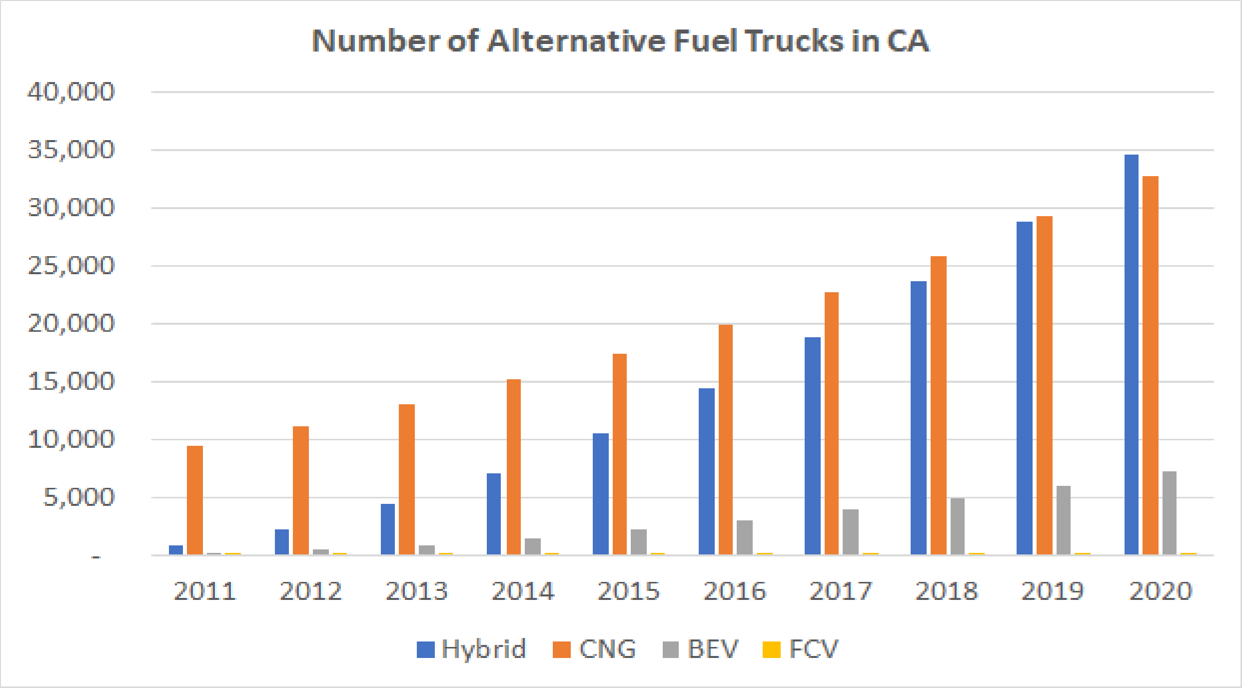


Figure 3.20. Number of Alternative Fuel Trucks in California

3.3.3 HDV VMT

According to the U.S. Department of Energy (DOE) [58], Class 8 HDVs drive the most miles per year per vehicle (Figure 3.21) and they are responsible for a disproportionate share of GHG emissions and local air pollution.

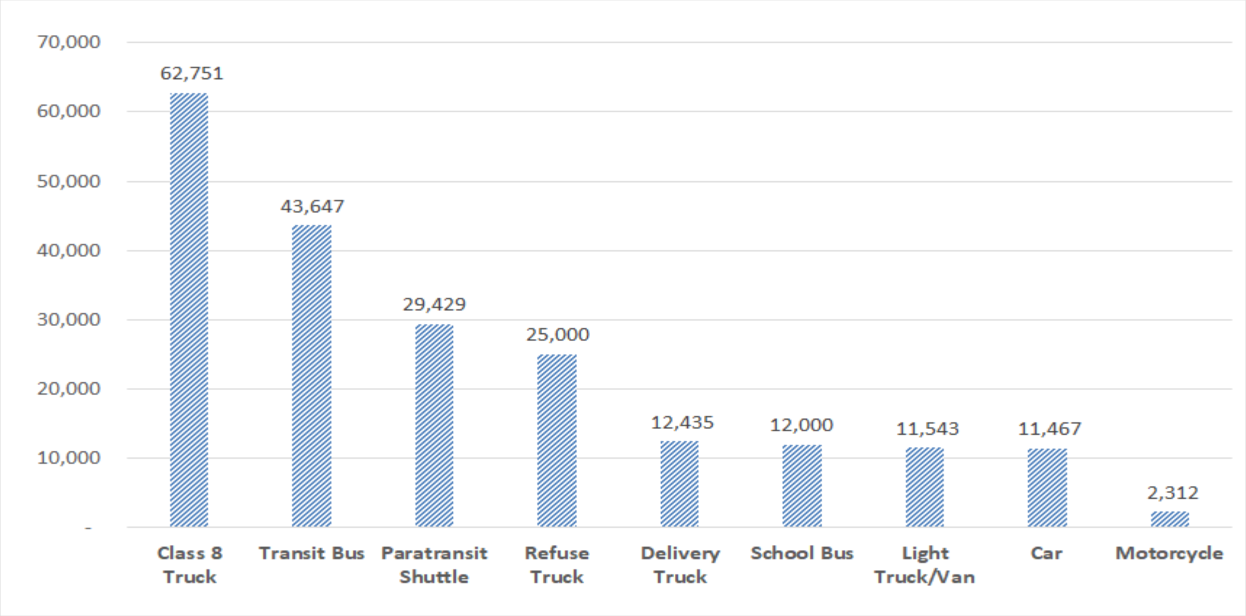


Figure 3.21. Average Annual Vehicle Miles Traveled per Vehicle by Major Vehicle Category

In the United States, VMT has increased over the long run with population and GDP, and has decreased at times with increased fuel prices [59]. Assuming that VMT growth will continue as business as usual (BAU), Figure 3.22 shows how daily VMT in California (broken down between light duty and heavy duty vehicles) might have changed without the COVID-19 pandemic.

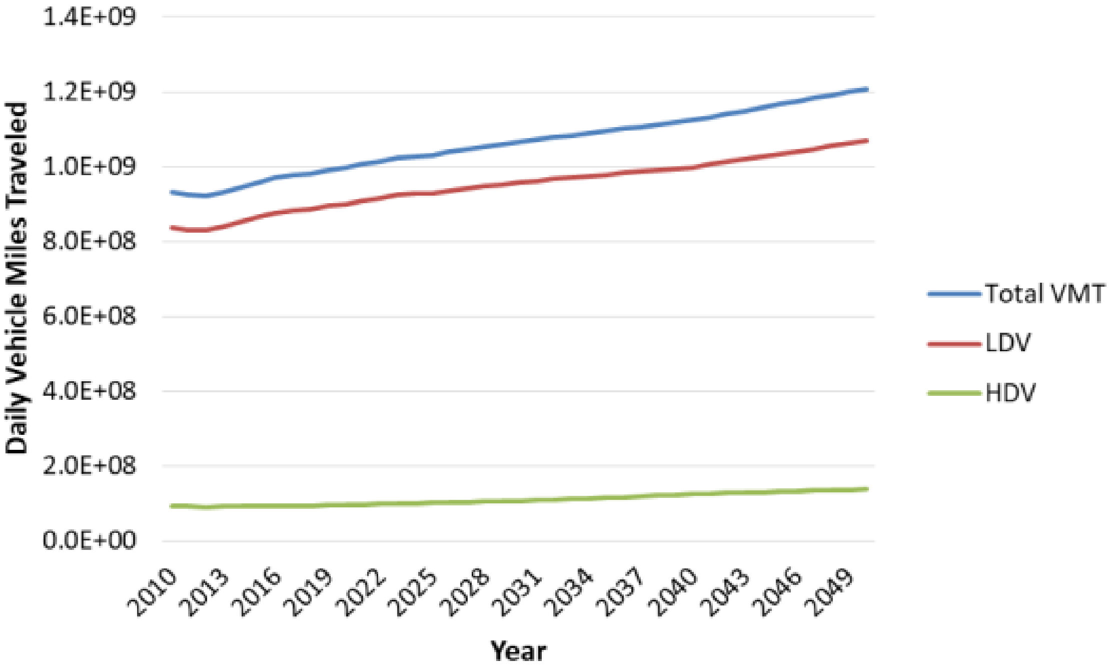


Figure 3.22. Daily VMT in California - ARB Baseline Projections

3.3.4 Alternative Fuel HDVs

Apart from HDVs powered by ICEs (ICE, 98% of which currently run on diesel fuel), several other powertrain technologies are likely to play a role in the future of HDVs: hybrid electric vehicle (HEV), PHEV, BEV, FCEV, and plug-in fuel cell electric vehicle (PFCEV) technologies.

HEVs add an electric motor and batteries to an ICE to improve energy efficiency. At low speeds, HEVs can run on their electric motor which is more efficient than their ICE and reduces GHG emissions. Moreover, when a HEV truck needs to brake, the electric motor can be run in reverse to slow the truck down, storing some energy in the battery and extending brake-pad life.

PHEVs are a variation on HEVs. The main differences are that they (1) can be recharged by an external electricity source when idle, and (2) have larger batteries, which extend their electric-only range.

Whereas HEVs and PHEVs have both an ICE and an electric motor, BEVs are powered only by electric motors and are equipped with larger batteries. BEVs are more efficient than similar vehicles with other types of powertrains, and they generate no air pollution or GHGs during their operation (the production of the electricity used to recharge their batteries may, however, generate both depending on the electric grid and when and where a BEV is charged). However, batteries are still relatively expensive and can add substantially to the weight of a vehicle therefore decreasing its useful load in certain applications. Charging time also remains an obstacle. Nevertheless, BEVs are under consideration for a number of vocations including transit buses, local delivery, drayage trucks, refuse trucks, and even long-haul trucks, including more than a dozen models currently available through the Heavy Vehicle Incentive Program.

An alternative technology to BEVs are FCEVs, which together can provide a broader zero-emission HDV strategy. In FCEVs, batteries are also included but with most power typically provided by a fuel cell system, which is an electrochemical device that converts the chemical energy of a fuel (typically hydrogen) and an oxidizing agent (typically oxygen) into electricity through a pair of redox reactions via proton exchange membranes. That electricity is sent to electric motors that propel the vehicle. Because hydrogen has a low volumetric density, it must be compressed and stored in a pressurized tank. To enhance their energy efficiency, FCEV HDVs, like battery-electric HDVs, will be equipped with regenerative braking. Like BEVs, FCEVs emit no air pollutants when they operate. We note that currently almost all of the hydrogen produced in the U.S. comes from the conversion of NG, which releases GHGs. California requires at least one-third of the hydrogen sold at fueling stations subsidized by the state to come from a renewable feedstock. Like ICE HDVs, FCEVs take little time to recharge. However, the lack of refueling infrastructure and vehicle weight are obstacles that still need to be overcome.

Finally, PFCEVs are an option that would borrow from FCEVs and PHEVs. They operate like PHEVs, but instead of an ICE, they are equipped with a fuel cell system like an FCEV. This makes PFCEVs more efficient than PHEVs as it removes the relative inefficiency of an ICE, but these vehicles are slightly more complex than FCEVs (although they offer more flexibility). These vehicles are not yet commercially available.

3.3.5 EV deployment

Zero-emission HDVs are an emerging market. Several automakers are already offering some vehicles for specific vocations, but the bulk of new offerings are yet to come. Table 3.4 shows some current and announced offerings by make and vehicle class.

Table 3.4. Examples of Heavy-Duty Zero-Emission Vehicles and Technical Specifications

Vehicle Make & Model	ZEV type	Vehicle type	Class	Battery size (kWh) H_2 capacity (kg)	Estimated fuel efficiency (kWh/mi or mi/kg)	Range
BYD	BEV	Bus	7, 8	324, 500	>1.86, >1.97	156, 255
BYD	BEV	Day Cab	8	435	>2.47	124 (full-load) 167 (half-load)
BYD	BEV	Cab chassis / step van	6	221	>1.68	124 (full-load)-125
Cummins*	BEV	Truck	7	140	>1.33	100-300
Daimler / Mercedes*	BEV	Truck	7	240	>1.84	≤124
Einride*	BEV	Autonomous truck	8	200	1.6	124
Lightning Systems	BEV	Van	2B-3	43, 86	0.55	60, 120
Navistar eStar**	BEV	Van	3	80	0.74	99.4
Smith Newton**	BEV	Truck	6	80, 120	1.34	60, ≤150
Smith Newton**	BEV	Van	6	80	1.41	99.4
Tesla*	BEV	Truck	8	800 (est.)	<2	300, 500
Zenith Motors	BEV	Van	2B-3	51.8-74.5	>0.65	80-135
Proterra	BEV	Bus	7-8	220, 440	1.46-2.32	93-234
Phoenix Motorcars	BEV	Flatbed	4	105	>1.0	100
Nikola / Bosch*	FCEV	Truck	8	240 kWh, 9 kg	Not available	500-750
Toyota / Kenwood	FCEV	Truck	8	12 kWh, 40 kg	6 mi/kg	200, 300 (Gen 2)
Van Hool / UTC Power**	FCEV	Bus	8	53 kWh, 50 kg	4.79 mi/kg	240 (est.)
US Hybrid	FCEV	Step van	3	28 kWh, 9.78 kg	1.18-1.47 kWh/mi, 12.8 mi/kg	125

Notes.
1) Range assumes 95% discharge of battery capacity
2) *, ** denote respectively announced and on-road tested vehicles
Range assumes 95% discharge of battery capacity. *, ** respectively denote announced and on-road tested vehicles (Source: Forest, K., 2019).

The adoption of these vehicles over time depends on a number of factors, including purchase and operating costs, refueling infrastructure availability, reliability, and the relative costs of alternatives. We note that the evolution of purchase and operating costs depend on the pace of technological progress and adoption.

3.3.6 Fostering the adoption of alternative fuel HDVs

There are currently dozens of policies, programs, and funding opportunities in California and the US targeting emissions reductions from the HDV sector, many of which are trying to get vehicle owners to replace their diesel trucks with zero-emissions versions. A summary of the main programs is presented in Table 3.5. While programs range in scope and funding mechanisms (e.g., voucher, credits, loan), some of the more relevant programs for this project include the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP), the Carl Moyer Memorial Air Quality Standards Attainment Program, and the Volkswagen Diesel Emissions Environmental Mitigation Trust. Most funding opportunities aim at reducing the high capital costs of low carbon/zero carbon vehicles and related infrastructure and accelerating their deployment. The Low Carbon Transit Operations Program (LCTOP) and the Transit and Intercity Rail Capital Program (TIRCP) fund clean transit, including electric buses.

While not a grant program, the federal Renewable Fuel Standard (RFS) and the California Low Carbon Fuel Standard (LCFS) programs provide credit-based incentives based on dispensed fuel amounts. This decreases the fuel costs for alternative fuel HDVs.

Although having many incentive programs is useful in principle, and air districts are available to assist throughout the process, navigating funding programs and estimating their cost implications can be complex and may deter some truck owners, especially small owner-operators. A couple of tools are available to assist them in this process. The Funding Finder Tool from CALSTART provides a filterable list of available funding sources to support heavy-duty alternative fuel vehicle (AFV) adoption and infrastructure build-out [60]. The HVIP Total Cost of Ownership estimator calculates total cost of ownership (TCO) for program-eligible HDVs [61]. While helpful, these tools are limited in scope, and there remains a need for providing more comprehensive guidance to fleet operators.

The current reduction in fossil fuel prices has temporarily diminished the economic competitiveness of alternative fuels. In general HDV owners and operators focus on TCO [62]. In addition to the availability of various incentives that lower the purchase price of alternative fuel trucks, TCO also depends on fuel costs, maintenance costs, and reliability. The availability of refueling infrastructure is also important but depends on truck vocation. For example, public refueling infrastructure may not be as critical for HDVs on fixed routes, such as urban buses or garbage trucks.

Table 3.5. Summary of HDV incentive programs

Program Name	Agency / Organization	Program Description
Carl Moyer Memorial Air Quality Standards Attainment Program (Carl Moyer Program)	CARB; All 35 Air Quality Management Districts (AQMDs)	Replacement, new purchase, repower, and retrofit trucks to reduce near-term air emissions; scrappage required. https://ww2.arb.ca.gov/our-work/programs/carl-moyer-memorial-air-quality-standards-attainment-program
Air Quality Improvement Program (AQIP); Low Carbon Transportation Program	CARB	Focuses on reducing criteria pollutants, diesel particulate emissions, and concurrent GHG emissions; Assembly Bill (AB) 32 Cap & Trade revenues applied to clean vehicle and equipment projects (mostly) for long-term GHG emissions reductions; https://ww2.arb.ca.gov/our-work/programs/low-carbon-transportation-investments-and-air-quality-improvement-program/low-1
Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP)	CARB	Reduces up-front cost of cleaner, more efficient trucks and buses. HVIP works with dealers so the voucher incentive is applied directly at the time of purchase https://www.californiahvip.org/
Truck Loan Assistance Program	CARB	Focus is on near-term diesel emission reductions; funding so far has been for lower emission combustion vehicles. SB 1 allows only clean trucks to be registered with the California DMV. https://ww2.arb.ca.gov/our-work/programs/truck-loan-assistance-program
Low Carbon Fuel Standard (LCFS)	CARB	Credit-based incentive program aimed at reducing transportation fuel carbon intensity by 20% by 2030. https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard
Volkswagen Diesel Emissions Environmental Mitigation Trust	State Mitigation Trust and the Indian Tribe Mitigation Trust	Funding of five categories of projects (1) Freight and marine; 2) ZE transit, school, and shuttle buses; 3) ZE Class 8 freight and port drayage trucks; 4) LD ZE infrastructure, hydrogen; and 5) LD ZE infrastructure, electric) as approved by CARB.

Finally, although this section focuses on on-road vehicles, we note the availability of the Clean Off-Road Equipment Voucher Incentive Project, which is designed to accelerate the deployment of zero-emission off-road equipment by subsidizing its higher cost compared to conventional off-road equipment [63].

3.4 Vehicle miles traveled (VMT)

Reducing VMT in California from light, medium, and heavy-duty vehicles is a critical part of reducing transportation system GHG emissions. VMT is defined as miles of travel by all individual vehicles (light, medium, and heavy duty), excluding passenger and freight rail and off-road modes. Future trends in VMT in California can be influenced through various types of strategies and policies. These include land use policies, roadway and toll pricing, increased use of transit, policies to support tele-work, strategies to increase micromobility and "active transportation" (biking and walking), policies to regulate transportation network companies (TNCs) and constrain their VMT, and strategies addressing the VMT of freight and goods delivery.

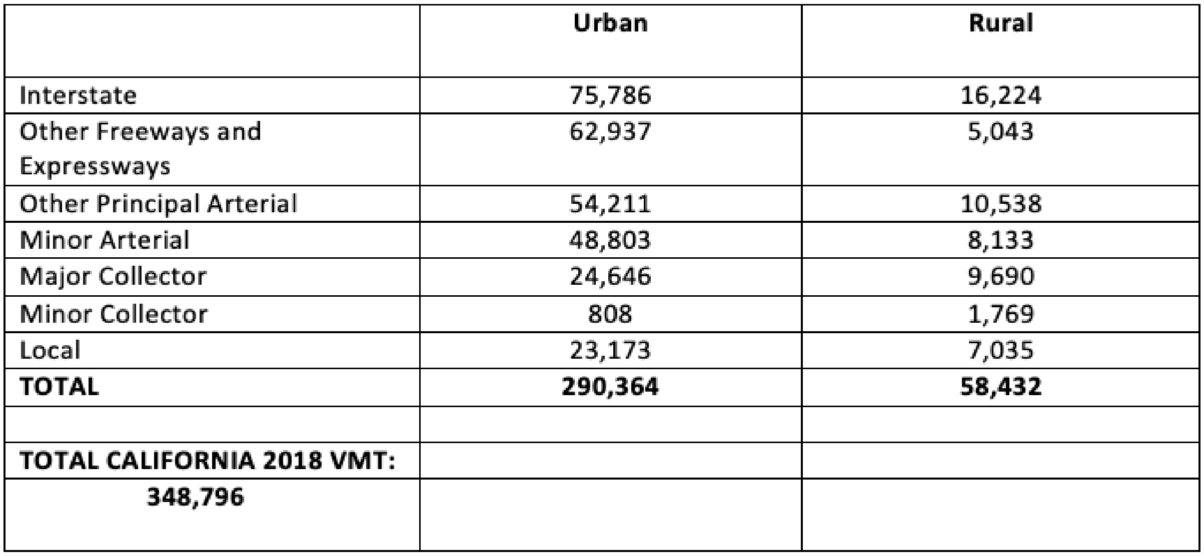
Currently, VMT is mostly examined and addressed at the metropolitan planning organization (MPO) level. SB375 requires MPOs to examine VMT and per capita GHG emissions targets as part of their planning process. Under current law, they must include sustainable communities strategies (SCS) plans to achieve CARB's targets for their region as part of their long range plans. To do this they consider: 1) land use planning that considers the Regional Housing Needs Assessment and protection of sensitive resources; 2) analysis of transportation networks including highways, transit and local streets and roads; 3) transportation demand management strategies; and 4) transportation system management programs. The 18 MPOs in California have prepared these SCS plans, to be updated every 4-5 years with measurement of progress toward emission reduction, and updated policy and implementation plans.

The following sections describe various topics related to VMT and potential strategies for managing per capita VMT in California. These topics interact in complex ways, such as linkages between micromobility and active modes and the use of transit, land use and jobs/housing balance and mobility patterns, etc. Discussed first in this section are general VMT trends and VMT by travel mode. This is followed by discussion of shared mobility systems and VMT impacts, and then the rise of TNCs and impacts on VMT. Next, land use issues and strategies are discussed, followed by sections on transit systems, pricing strategies, and truck/freight VMT. A final section describes state tools that are useful for VMT analysis along with a new state strategy for assessing system performance based on VMT impacts rather than the level of service of the network.

3.4.1 Total VMT

First, according to the U.S. Department of Transportation (DOT), total California VMT in 2018 by all vehicle types was nearly 350 billion miles. This represents about 9% of all of the 3.26 trillion VMT in the U.S. in 2018. The next highest states are Texas with 282 billion VMT and Florida with 222 billion VMT. The majority (about 83%) of VMT in California came from urban regions, and the balance (17%) from rural areas. Table 3.6 provides a more granular breakdown of California VMT data.

Table 3.6. VMT by Functional Road Category in California - 2018 (millions)[10]



	Urban	**Rural**
Interstate	75,786	16,224
Other Freeways and Expressways	62,937	5,043
Other Principal Arterial	54,211	10,538
Minor Arterial	48,803	8,133
Major Collector	24,646	9,690
Minor Collector	808	1,769
Local	23,173	7,035
TOTAL	**290,364**	**58,432**
TOTAL CALIFORNIA 2018 VMT:		
348,796		

Source: U.S. DOT, 2018 [64]

As shown below (Figure 3.23), California's VMT has only increased slightly to about 8,700 miles per capita since dipping around 2009 during the financial crisis to about 8,500 miles per capita. By comparison, the U.S. national average has rebounded nearly to peak levels of about 10,000 miles per capita, having dipped to around 9,400 in 2009-10.

VMT analysis conducted by the Eno Center for Transportation as shown in Figure 3.23(a) compares the evolution of per capita VMT in some states that in 1981 had similar VMT to the national average. Figure 3.23(b) depicts VMT trends for a different group of four states that had somewhat higher or lower per capita VMT than the U.S. average in 1981. States such as Missouri, Mississippi, and West Virginia have generally much higher per capita VMT than California, whereas Washington VMT levels are about 6-7% lower per capita than in California (Figure 3.23). California had the 10th lowest and Washington had the 6th lowest per capita VMT of any state in 2017, and Mississippi had the 4th highest and Missouri the 7th highest amounts. VMT levels in Missouri have rebounded to higher than their previous peak, and in Mississippi they have rebounded by several hundred miles per capita but not to the level of the peak in around 2007, similar to West Virginia [65].

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[10] Note: Arterials provide direct, relatively high speed service for longer trips and large traffic volumes. Collectors provide a bridge between arterials and local roads. Collectors link small towns to arterials as well as collect traffic from local roads. Local roads provide direct access to individual homes and farms. Arterials and Collectors are further differentiated into Major or Minor categories based on classification by local officials.

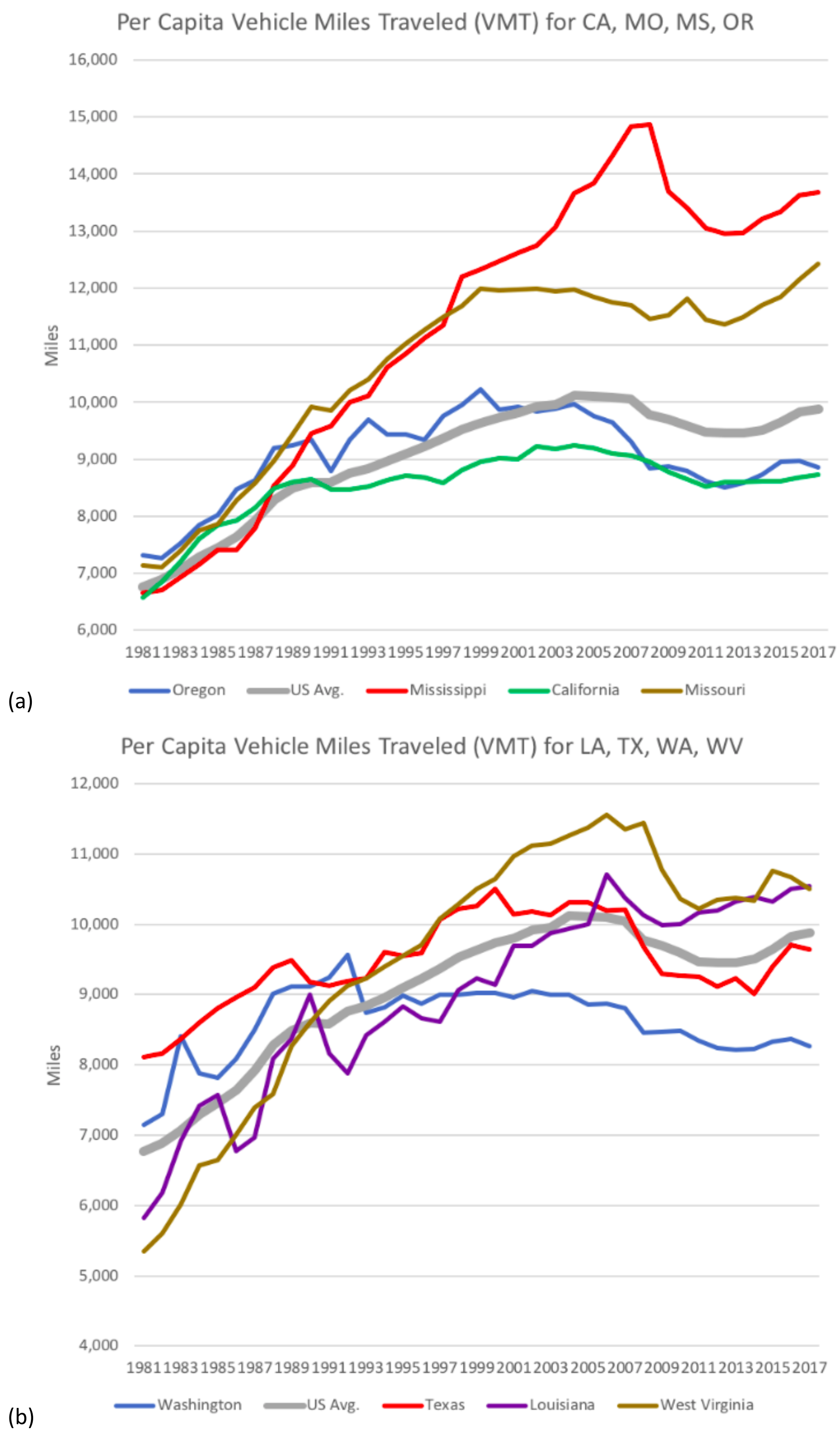


Figure 3.23. Per-Capita VMT Trends for U.S., California, and Example States - Eno Transp. Found. (2019) [65]

Shown below in model runs performed by UC Irvine below are modeled results for daily VMT from each California county from the California Statewide Travel Demand Model (CSTDM) (Figure 3.24). Also note that these VMT estimates are for passenger vehicles only whereas that data in Figure 3.23 and Table 3.7 represent total VMT including heavier duty vehicles. The chart gives a sense of the modeled (i.e., approximate) distribution of VMT around the state on a per-county basis, with counties of varying size and population.

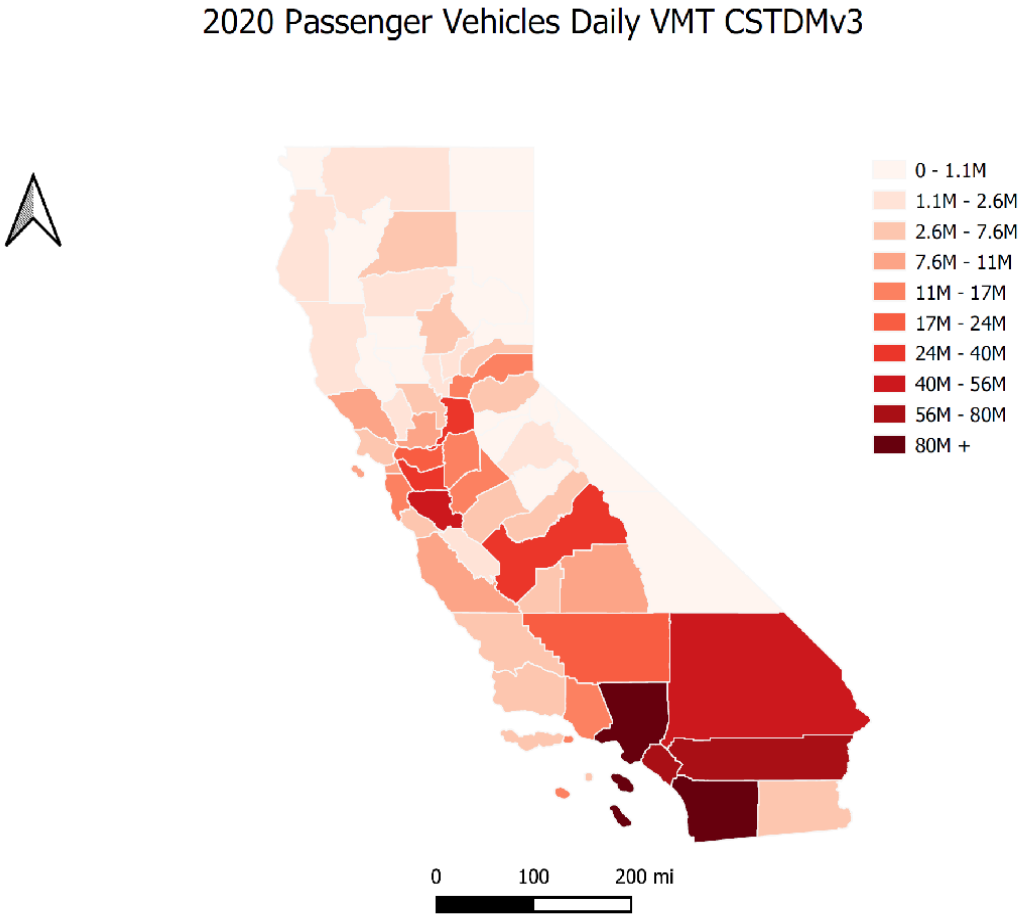


Figure 3.24. Modeled Daily VMT for Light-Duty Cars in California by County from CSTDM

3.4.2 VMT by Travel Mode

Figure 3.25 below shows trends in U.S. VMT over the last 118 years, broken down by vehicle mode (including all passenger vehicles (LDVs) as well as trucks, buses, and motorcycles). Figure 3.25 shows that passenger vehicles have long dominated aggregate VMT on U.S. roads. In 2018, passenger vehicles comprised 89% of U.S. VMT. Truck traffic was a distant second at 9%, followed by motorcycles (1%) and buses (1%).

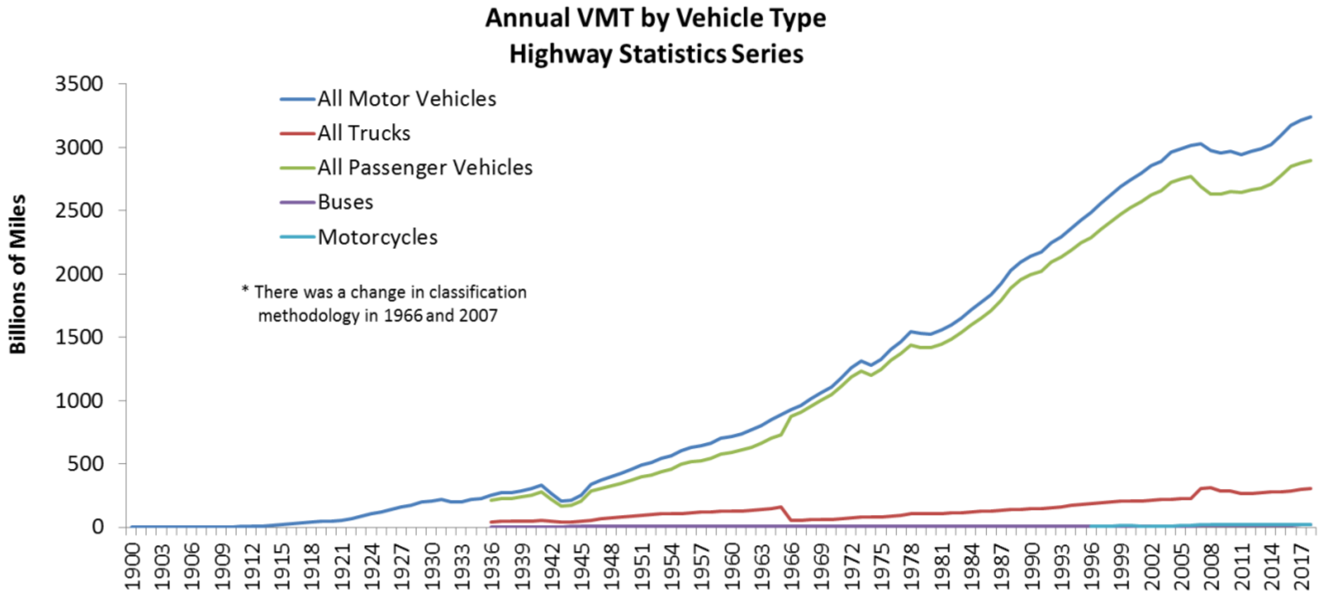
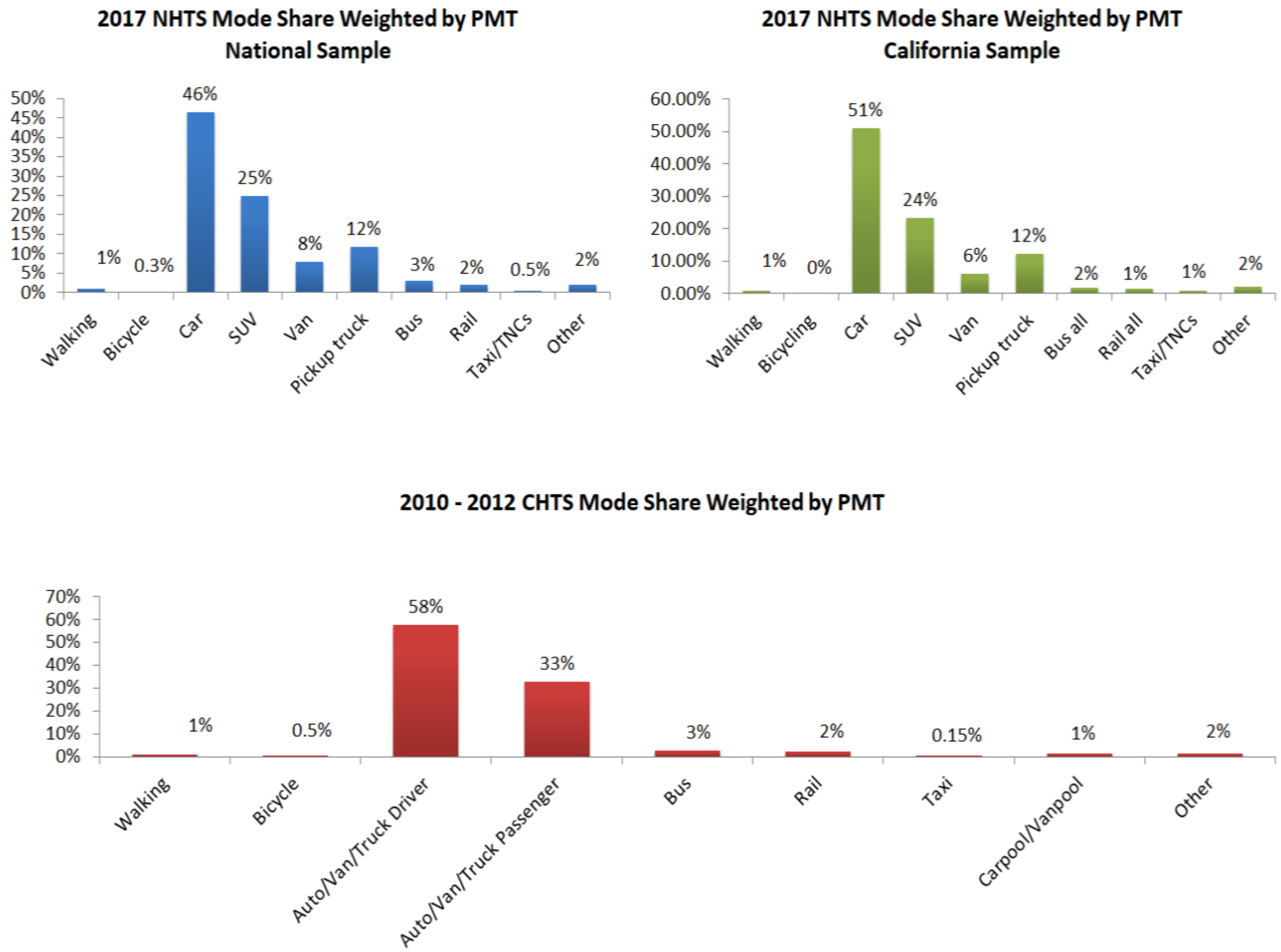


Figure 3.25. Trends in U.S. VMT by Mode (Data Source: U.S. DOT Office of Highway Policy Information, 1900 to 2018) [66].

The FHWA's Highway Statistics Series provides perhaps the most comprehensive time-series measurement of VMT of any resource. However, it does not contain information on non-motor vehicles (such as rail transit and bicycles), nor does it break out VMT by vehicle function (such as TNCs). For estimates of these measures, different data sources need to be consulted. Such sources include household surveys, such as the National Household Travel Survey (NHTS) and the California Household Travel Survey (CHTS). However, when assessing travel by modes that a passenger takes, the measure often used is "person miles traveled" (PMT) rather than VMT.

The latest NHTS was conducted in 2017 and the latest CHTS was conducted from 2010 to 2012. The NHTS also had a California sample, where additional California household samples were purchased by the state and Metropolitan Planning Organizations (MPOs). Data from these surveys provide a snapshot of travel behavior and distances by mode, but strictly for passenger travel. The distribution of mode by PMT for both surveys is shown below (Figure 26). The NHTS data are for the U.S. as a whole, the California households within the NHTS, and the CHTS.

The distributions are displayed in percentages for direct comparison, and have close alignment. Self-driven automotive modes in the NHTS survey cover 90% of PMT in the national sample, 93% in the California NHTS sample, and 91% of PMT in the CHTS. The PMT accounted for by other modes, including walking, bicycling, and public transit, are very similar across the three surveys. A small but notable difference is the increased use of taxis/TNCs in the NHTS (0.5% of PMT) relative to the older CHTS data (0.15% of PMT). This difference is likely driven by the expansion of TNCs that most notably occurred after the last CHTS was completed. The level of taxi/TNC use in the California NHTS and national sample is also very similar, 0.5% nationally as compared to 0.77% in California (rounded to 1% in the figure).



2017 NHTS Mode Share Weighted by PMT
National Sample

2017 NHTS Mode Share Weighted by PMT
California Sample

2010 - 2012 CHTS Mode Share Weighted by PMT

Figure 3.26. Passenger-Miles Traveled by Mode in National and California Datasets

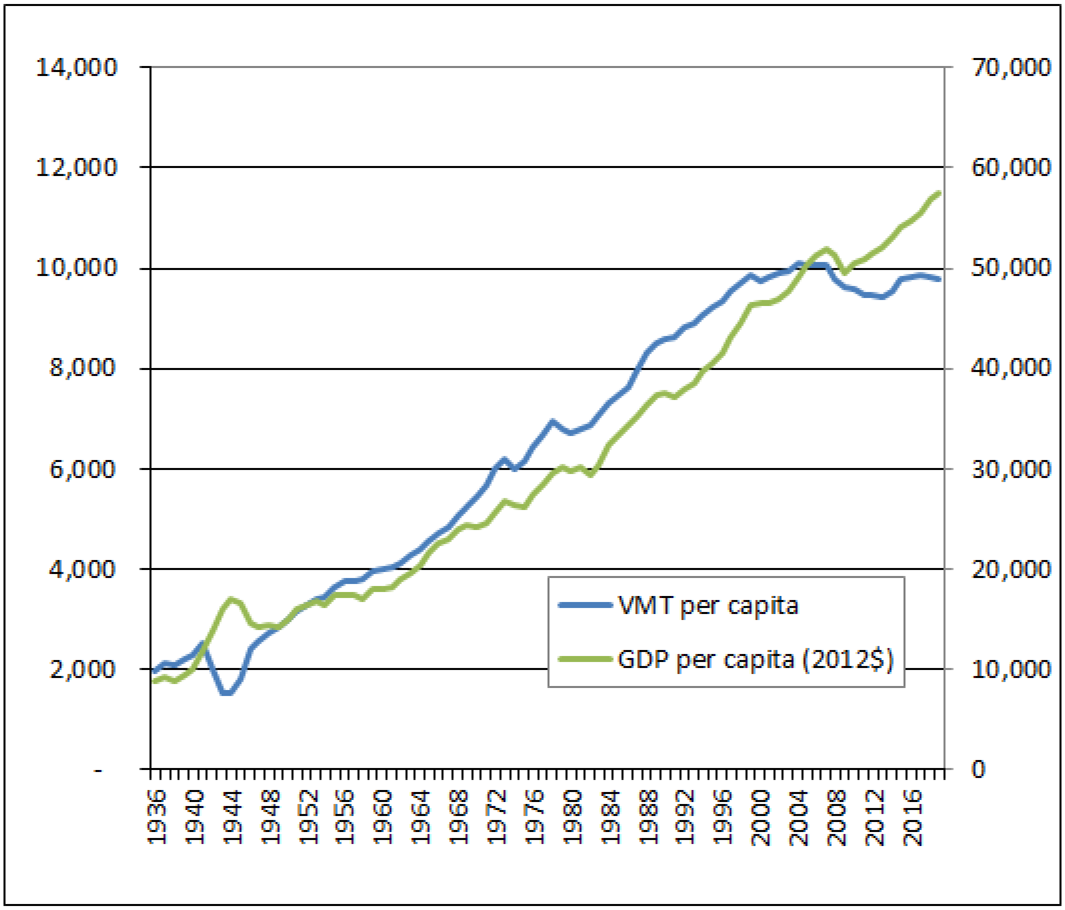


Figure 3.27. VMT per capita compared to GDP per capita from 1936 to 2016.

3.4.3 VMT impacts of shared mobility

Shared mobility has proliferated throughout California and the broader nation during the 21st century. The modern shared mobility industry in the United States arguably began with carsharing and expanded into bikesharing, TNCs (also known as ridehailing and ridesourcing), dockless micromobility (scooters and bicycles), and microtransit. Sometimes, shared mobility modes are used to connect to other modes. There is also limited vertical integration within the industry, in that operators of one mode have not operated other modes. TNCs have more recently broken this mold, in that Uber and Lyft have both invested in micromobility (bikesharing and e-scooters). However, Uber's recent divestiture of its micromobility operator is a reversal of this trend. Research over more than two decades has evaluated the degree to which these modes impact travel behavior and vehicle ownership of users. Impacts of shared mobility vary by mode, and understanding of more recently emerged modes is still evolving. Insights can be gained from summaries of research that is currently available. Table 3.7 and Table 3.8 present a summary of selected research on carsharing as excerpted from [67]. The summarized impacts are focused on vehicle ownership and VMT change.

Table 3.7. Summary of Roundtrip Carsharing Impact Studies

Operator and Location	Authors, Year	Number of Vehicles Removed from the Road Per Carsharing Vehicle	Members Selling Personal Vehicle %	Members Avoiding Vehicle Purchase %	VMT/VKT Change % per Member
Round Trip Carsharing Studies					
Short-Term Auto Rental - *San Francisco, CA*	(Walb & Loudon, 1986) [68]		15.4	43.1	
Arlington Carsharing (Flexcar and Zipcar) *Arlington, VA*	(Price & Hamilton, 2005) [69]		25	68	-40
	(Price, DeMaio, & Hamilton, 2006) [70]		29	71	-43
Carsharing Portland - *Portland, OR*	(Katzev, 1999) [71]		26	53	
	(Cooper, Howe, & Mye) [72]		23	25	-7.6
City Carshare - San Francisco, CA	(Cervero, 2003) [73]		2.5	60	-3.0a/- 58.0b
	(Cervero & Tsai, 2004) [74]	6.8	29.1	67.5	-47.0a/ 73.0b
	(Cervero, Golub, & Nee, 2007) [75]				-67.0a/ 24.0b
PhillyCarshare - *Philadelphia, PA*	(Lane, 2005) [76]	10.8c	24.5	29.1	-42
TCRP Report – Surveyed Members of More Than Nine Carsharing Companies - *North America*	(Millard-Ball, ter Schure, Fox, Burkhardt, & Murray, 2005) [77]				-63
Surveyed Members of Eleven Carsharing Companies	(Martin & Shaheen, 2011) [78]				-27
	(Martin, Shaheen, & Lidicker, 2010) [79]	9.0-13.0	23	25	
Zipcar - *U.S.*	(Zipcar, 2005) [80]	20	32	39	-79.8
Modo - Vancouver, Canada	(Namazu & Dowlatabadi, 2018) [81]	5		55	

Source: Shaheen et al., 2019 [67]

Table 3.8. Summary of One-way and Person-to-Person (P2P) Carsharing Impact Studies

Operator and Location	Authors, Year	Number of Vehicles Removed from the Road Per Carsharing Vehicle	Members Selling Personal Vehicle %	Members Avoiding Vehicle Purchase %	VMT/VKT Change % per Member
One Way Carsharing Studies					
Car2Go (U.S. and Canada)	(Martin & Shaheen, 2016) [82]	7.0-11.0	2.0-5.0	7.0-10.0	-6.0 to -16
Car2Go (Vancouver, Canada)	(Namazu & Dowlatabadi, 2018) [81]	6		55	
Car2go (San Diego, CA)	(Shaheen, Martin, & Bansal, 2018a) [83]				
Peer to Peer Carsharing					
Getaround, RelayRides (Turo), and eGo Carshare *U.S.*	(Shaheen, Martin, & Bansal, 2018b) [84]		0.14	0.19	
Getaround Portland, OR	(Dill, McNeil, & Howland, 2017) [85]			0.44	

Source: Shaheen et al., 2019 [67]

Overall, carsharing studies overwhelmingly find that carsharing reduces vehicle ownership and overall household VMT. Net changes in VMT at the personal or household level (depending on the study) have ranged from about 8% to upwards of 80%. Most members of carsharing exhibit very limited impacts from carsharing, while others can experience more profound effects. For example, Martin and Shaheen found that the majority of carsharing users actually increased their emissions as a result of exposure to carsharing [78]. Such users were generally carless, and hence drove more as a result of having access to a vehicle. However, the individual increase in VMT was small on a per user basis. At the same time, a minority of users reduced their VMT by amounts far greater, due to shedding of personal vehicle, or suppressing the need to acquire a personal vehicle. The resulting reduction in VMT from these actions was found to be much greater on an individual basis, and collectively resulted in a net reduction of household VMT overall. This dynamic has generally been found and confirmed in various subsequent work evaluating the overall household-level VMT impacts of carsharing.

A number of studies have also been conducted evaluating the impacts of bikesharing and TNCs. These studies find a mixture of impacts with respect to how bikesharing and TNCs influence mode use and VMT. For example, Table 3.9 and Table 3.10 summarize the impacts noted from bikesharing studies, as excerpted from Shaheen et al. [67]. The table shows the program under study and selected calculations of impact that were reported by the studies. In general, shared micromobility has been shown to have some significant impacts on mode use and the resulting change in VMT. One note about the studies is that they do not cover the VMT imposed by systems as they move bicycles around as part of rebalancing operations. Rather, these studies focus on the demand side of activities and travel behavior changes due to shared micromobility services.

Table 3.9. Summary of Docked Bikesharing Impact Studies

Study Name ***Location***	**Authors, Year**	**Mode Use**	**Environment**
Capital Bikeshare Member Survey Report *Washington, D.C.*	LDA Consulting, 2013 [86]	After joining bikesharing: - 54% of respondents started or ended a bikesharing trip at a Metrorail station in the last month - 50% drove a car less often - 60% used a taxi less often - 61% ride Metrorail less often and 52% ride a bus less often - 52% decreased walking*	After joining bikesharing: - ¼ of respondents reduced their driving miles - On average, driving was reduced by 198 miles per year
Bikeshare's impact on car use: Evidence from the United States, Great Britain, and Australia Washington, D.C. and Minneapolis-St. Paul	Fishman et al., 2014 [87]	**Washington, D.C.:** - 45% replaced public transit - 31% replaced walking - 7% replaced driving a vehicle - 6% replaced personal bicycle - 6% replaced taxi - 4% generated new trips **Minneapolis-St. Paul:** - 20% replaced public transit - 37% replaced walking - 19% replaced driving a vehicle - 8% replaced personal bicycle - 3% replaced taxi - 8% generated new trips**	**Estimated car travel reduction per bike of:** - 153 mi (247 KM) in Washington, D.C. - 83 mi (135 KM) in Minnesota
Bikeshare's impact on active travel: Evidence from the United States, Great Britain, and Australia *Washington, D.C. and Minneapolis-St. Paul*	Fishman et al, 2015 [88]	**Bikesharing trips replaced sedentary modes by:** - 42% in Minneapolis-St. Paul. - 58% in Washington, D.C.***	

Study Name ***Location***	**Authors, Year**	**Mode Use**	**Environment**
Are bikeshare users different from regular cyclists? *Washington, D.C.*	Buck et al., 2013 [89]	**For annual members:** - 45% replaced public transit - 31% replaced walking - 7% replaced driving a vehicle - 6% replaced personal bicycle - 6% replaced taxi - 4% generated new trips **For short-term users:** - 53% replaced walking - 35% replaced public transit - 5% replaced taxi - 2% replaced personal bicycle - 2% generated new trips - 2% other - 1% replaced driving a vehicle	

Shaheen et al., 2019 [67]

* Respondents asked if they had changed their use of any five non-bicycle types of transportation.

** Thinking about your last journey on bikeshare, which mode of transport would you have taken had it not existed?

*** Respondents asked what alternative mode they would typically have used for that trip before bikesharing was introduced.

Table 3.10. Summary of Dockless Bikesharing Impact Studies

Study Name ***Location***	**Authors, Year**	**Mode Use**	**Environment**
Dockless Bikesharing			
Electric Bikesharing in San Francisco: An Evaluation of JUMP Electric Bikesharing during an Early Pilot Deployment *San Francisco, CA*	Shaheen et al., forthcoming [90]	- 10% replaced driving a vehicle - 14% replaced transportation network company trip (TNC, e.g., Lyft, Uber) - 26% replaced public transit - 8% replaced walking - 24% replaced personal bicycle - 4% replaced a motorcycle or scooter - 1% replaced scooter sharing - 5% other+	
Dockless Scooter Sharing			
2018 E-Scooter Findings Report *Portland*	Portland Bureau of Transportation, 2019 [91]	- 37% replaced walking - 19% replaced driving a vehicle - 15% replaced a taxi or TNC - 5% replaced personal bicycle++	Estimated e-scooters prevented automobiles from emitting 122 metric tons of carbon dioxide during the four-month pilot, equivalent to removing nearly 27 average passenger vehicles from the road for a year.

Shaheen et al., 2019 [67]
+ If JUMP were not available, how would you have made this trip instead?
+ Respondents thought about what mode they would have used for their last e-scooter trip, if the e-scooters had not been available.

Shared e-scooters have emerged as the most recent micromobility mode. E-scooters are often mixed in with other dockless modes, although there are prominent systems that focus exclusively on e-scooters. A number of studies have evaluated the impact that e-scooters have had on mode shift. Many of those studies have been city specific and asked questions probing the trip that would have been taken in the absence of e-scooter availability. As noted in Table 3.10, e-scooters replace active modes such as walking and bicycling, but also driving a personal vehicle or taxi/TNC use. Other city-specific studies have uncovered similar findings. For example, in Chicago, it was found that 32% of survey respondents would have taken ridehailing and 11% would have driven [92]. A study of bikesharing in Greater Sacramento looked at how s-bikes and e-scooters impacted behavior, and found that 35% of e-bike trips substituted for car travel [93]. These findings suggest that e-scooter and e-bike provisions are reducing personal automobile use and associated VMT.

Since 2012, TNCs have further expanded shared mobility access to urban and rural regions across California. A number of studies have begun to shed light on VMT impacts. A summary of VMT-related findings from three studies are presented in Table 3.11 as excerpted from Shaheen et al. [67]. These studies explored how TNCs impacted on-road VMT within two major U.S. cities: New York City and San Francisco. These studies focus on the

VMT of TNC vehicles. They do not comment on reductions in VMT that may result from shifts in travel behavior and vehicle ownership. However, their estimates include the operating phases of TNCs, including deadheading and traveling to pick up passengers. This mileage includes shifts to TNCs from active modes and public transit. The results of these studies suggest that the aggregate amount of TNC-induced VMT on urban roads within these major markets is notable.

Table 3.11. Summary of Studies on VMT from TNC Vehicles

City ***Study Author*** **Data Time Period**	**Key Trip Metrics**	**Key Mileage Metrics**
San Francisco, CA *SFCTA* 1 month, late-2016 [94]	*TNC trips comprise* • **15% of total vehicle trips** (intra-SF, avg. weekday) • **9% of total person trips** (intra-SF, avg. weekday)	*TNC mileage comprises...* • **20% of intra-SF VMT** (avg. weekday) • **6.5% of total VMT** (avg. weekday) • **10% of total VMT** (avg. Saturday)
New York City, NY *Schaller Consulting* Full year, 2016 [95]	*TNC trips comprise…* • 80 million vehicle trips (in 2016) • 133 million person trips (in 2016)	*TNC mileage comprises…* • **7% of total VMT** (in 2016) *TNC mileage equates to an estimated increase of…* • **3.5% citywide VMT** (in 2016) • **7% VMT** in Manhattan, western Queens and western Brooklyn (in 2016)
New York City, NY *Schaller Consulting* June 2013 and June 2017 [96]	*TNC/taxi trips increased by…* • **15% between June 2017 and June 2013** (Manhattan CBD, avg. weekday) • **133 million person trips** (in 2016)	*TNC/taxi mileage increased by…* • **36% between June 2017 and June 2013** (Manhattan CBD, avg. weekday)

Shaheen et al., 2019 [67]

Research has shown that there are different types of users of TNC vehicles that relate to their impact on energy consumption. Circella et al. [55] noted that there exist four latent classes of modality styles of TNC users, including drivers, active travelers, transit riders, and car passengers. They found that drivers, who generally have higher vehicle ownership, have a relatively limited impact on energy consumption from TNC use. Active travelers, who generally have a low energy use profile, exhibited relatively high emissions from TNC. The VMT by mode is of course also context specific to land use. Urban regions show much higher mode shares for public transit, walking, bicycling, taxis, and TNCs. A recent study by Fehr and Peers reveals that TNCs have very different impacts on VMT depending on location [97]. The study examined traffic impacts from recent growth in TNC use in six urban areas, including the San Francisco Bay Area. TNC share of regional VMT ranged from 1.1% to 2.7%, with the highest value in the Bay Area. In core urban areas, the share of VMT from TNCs was as high as 12.8% in San Francisco. For comparison, the share of VMT from TNCs was 6.9% in Washington, DC, 7.7% in Boston, and as low as 1.9% in the core urban area of Seattle. Figure 3.28 below provides maps showing the primary study findings.

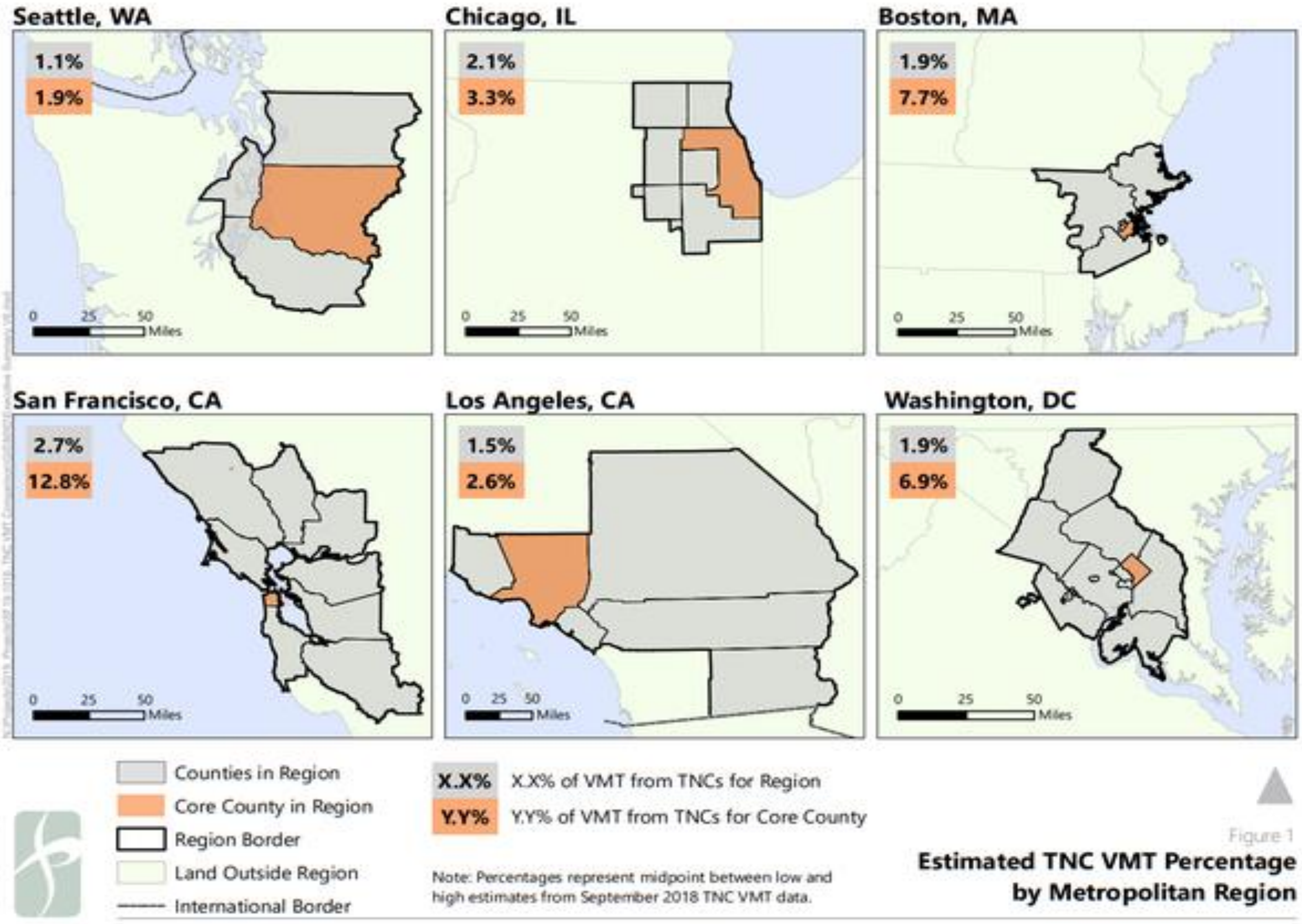


Figure 3.28. Estimated TNC VMT Percentage for Six U.S. Regions. Fehr and Peers (2019) [97].

Finally, studies of automated vehicles (AVs) have begun to emerge. At present AVs in California are being tested, but to date, there are no shared AVs in operation and no private AVs operating at higher than SAE Level 2 autonomy, which requires the driver to be prepared to intervene immediately. Several studies have been conducted evaluating how AVs might influence travel behavior, VMT, and fuel consumption. Some studies evaluate how AVs influence travel on specific populations. Other studies evaluate how a fleet of shared automated vehicles (SAVs) operating in an urban environment would impact emissions and personal vehicle ownership. These studies also explore the charging dynamics of such systems assuming the fleet will be electrically powered.

Harper et al. evaluated implications of AVs provided to specific types of underserved populations, including non-drivers, older adults, and adults with travel-restrictive medical conditions [98]. Their analysis showed that AVs provided to these populations increased annual LDV VMT by 14% overall. Most of this increase (65%) was from current adult non-drivers, while the remaining increase was roughly split between older drivers without a medical condition (16%) and adult drivers with travel-restrictive medical conditions (19%). Harb et al. [99] evaluated AV-induced changes in the travel behavior of populations who currently do not often drive, including retirees and children. The results showed that the service for these populations led to an 83% increase in VMT, 21% of which was with empty vehicles.

SAVs are generally simulated under a variety of assumptions about fleet operations. Increases in fleet size will change VMT as the larger fleet of SAVs would serve more people (sometimes in a pooled capacity) and drive more zero-occupancy miles. A number of studies suggest that SAVs could increase these zero-occupancy miles anywhere from 8% to 16% depending on the market penetration rate [100]–[102]. Commensurately, reducing fleet size could lower energy consumption and emission levels, although researchers disagree on the likely magnitude of these changes. Results from Fagnant and Kockelman [103] and Zhang et al. (2015) [104] suggest that SAVs would result in lower carbon monoxide (CO) and volatile organic compound (VOC) emissions, due to system efficiencies and fewer engine cold starts.

In addition to changing fleet size, dispatching right-sized SAVs could help reduce energy consumption and emissions further by allowing one and two-person trips to be served by smaller vehicles. Martinez and Viegas [105] report findings from a study of Lisbon suggesting that right-sizing SAV vehicles would result in a 40% reduction in GHG emissions. Greenblatt and Saxena [106] found that right-sized automated taxis operating on electricity could reduce GHG emission rates per distance by 94% as compared to current day conventional vehicles. Wadud et al. [107] found that vehicle right-sizing would result in up to a 45% reduction in energy use, based on use of conventional fuels. Notably, not all researchers believe that SAVs will have a positive environmental impact. For example, Lu et al. [108] concluded SAVs will result in higher energy consumption and GHG emissions as a result of increased VMT.

As experience shared mobility and autonomous vehicle systems grows, so too will the more collective understanding of their role and contribution to broader impacts on VMT. What is clear from the existing body of literature is that shared mobility has played a central role in innovative mobility services within urban and increasingly less dense land use environments. As they continue to evolve, such as through the implementation of automation, so too will the nature of their VMT impacts. Tracking these impacts will require continuity of research and collaboration with the industry, as well as continued engagement on issues of data, public transit integration, and municipal cooperation.

3.4.4 VMT and land use

Land use policies are an essential component of a package of strategies for reducing VMT. The relationship between travel behavior and land use has received much scholarly attention over the past three decades, partly to understand the extent to which VMT from private vehicle use can be reduced by changing the built environment in urban areas. Researchers have identified several characteristics of the built environment that can significantly impact travel behavior: population and employment density, land use mix, and street network connectivity. These characteristics determine the level of accessibility that individuals have to needed or desired destinations from their home or other locations and thus influence their travel choices [109]–[113]. A number of studies have found that characteristics of the built environment explain more than half of the VMT difference between compact urban and sprawling suburban neighborhoods after accounting for the fact that different kinds of people choose to live in different kinds of places (a phenomenon known as residential self-selection) [109]–[113].

Research on the relationship between the built environment and travel behavior is mostly cross-sectional, meaning that it shows how differences in the built environment are associated with differences in travel behavior. These studies do not directly show how travel behavior will change as a result of changes in the built environment. They can give an indication of how much change might be possible. A meta-analysis of over sixty empirical studies [110] found that the weighted-average elasticity of VMT with respect to each of density, land use mix, and street connectivity ranges from -0.04 to -0.12, suggesting that doubling each of these three variables could decrease VMT by ~25%. Regional accessibility, defined, for example, as the number of jobs accessible within 30 minutes of travel, appears to have a larger (in magnitude) elasticity (-0.15 to -0.22) [114]. While most empirical studies analyze travel at the neighborhood level, several studies have shown that metropolitan scale elasticities of various urban form variables are larger (ranging from -0.24 to -0.38) than neighborhood-level elasticities, and that population density matters [115]–[117]. Accounting for population distribution yields even larger effects. Indeed, a regional-scale study conducted by Lee and Lee (2020) [118] found a value of -0.63 for the elasticity of destination accessibility after controlling for self-selection.

It is important to note that while changes in the built environment may not be sufficient for meeting VMT reduction goals on their own, they are essential to this effort. Other strategies for reducing VMT, such as investments in transit systems and in bicycle and pedestrian infrastructure, depend on changes in the built environment. Transit systems, for example, depend on sufficiently high residential and employment densities. Walking and bicycling are viable as modes of transportation only when destinations are within walking and bicycling distance. Conversely, investments in alternatives to driving are essential to efforts to increase residential and employment densities.

Among measures of urban form, density has received considerable attention ever since the landmark study of Newman and Kenworthy (1989a, 1989b) [119], [120]. Researchers have also paid increasing attention to the location of employment centers in relation to residential areas to analyze commuting [121], [122]. The issue of jobs and housing balance is a critical one that the state is grappling with through various measures designed to encourage in-fill housing development, including provision of low-income units in larger development projects. Researchers have also proposed indices to measure sprawl at larger scales [123], and to capture various aspects of sprawl [124].

3.4.5 Transit systems in California

Data collected for the American Public Transportation Association (APTA) reports detailed transit-system operation and fuel use by type from over 80 transit agencies in California.

Table 3.12 summarizes key operational statistics for California transit agencies, including vehicles operated, passenger travel, cost and revenue per passenger, and total vehicle revenue miles. Data from 2015 and 2018 are presented to show changes over that period.

As shown, transit use and fare revenue dipped some from 2015 to 2018 with lower ridership levels and revenues, and small increases in vehicles operated and operating expenses. Vehicle revenue miles increased slightly from 2015 to 2018 but fare revenues relative to operating expenses dropped somewhat, along with total revenues. The implications of these trends, along with the recent drop in transit ridership due to COVID-19, suggests that in order to increase transit use in California as one VMT reduction measure, additional policy actions will be required such as subsidized transit passes for low-income groups and improvements to transit system efficacy through planning and system expansion.

Table 3.12. Operational Statistics for California Transit Agencies – 2015 / 2018

Statistic	Year 2015	Year 2018	Measure
Vehicles Operated in Maximum Service (VOMS)	18,447	19,022	Vehicles
Fare Revenues per Unlinked Passenger Trip	$2.31	$2.06	Dollars
Fare Revenues per Total Operating Expense	0.18	0.14	Ratio
Passengers per Hour	14.26	11.87	Passengers
Cost per Passenger	23.14	22.36	Dollars
Fare Revenues Earned	1,872,801,900	1,816,926,037	Dollars
Total Operating Expenses	6,274,286,314	7,360,370,696	Dollars
Unlinked Passenger Trips	1,435,298,779	1,293,074,046	Trips
Vehicle Revenue Miles	660,672,051	690,837,942	Miles

Source: APTA, 2015 and 2018 [124]

These transit agencies in California use a broad mix of fuels, including gasoline, diesel, liquefied petroleum gas (LPG), and liquefied natural gas (LNG) to biodiesel (BD), renewable diesel (RD), electricity, hydrogen, and miscellaneous types such as waste restaurant fry oil. Table 3.13 below presents fuel-type statistics for 2015 and 2018 as reported to APTA by the 82 reporting transit agencies. As shown, gasoline and diesel use have remained fairly constant, BD use has dropped somewhat, while battery electric bus electricity use has more than doubled.

Table 3.13. Fuels Types and Amounts Used by California Transit Agencies – 2015 / 2018

Fuel Type	Year 2015	Year 2018	Measure
Diesel	46,047,172	48,412,390	Gallons
Gasoline	20,694,710	18,637,749	Gallons
Liquefied Petroleum Gas	7,532,347	2,099,190	Gallons
Compressed Natural Gas	86,560,355	88,910,762	Gallons
Biodiesel	303,686	66,584	Gallons
Other Fuels (Including hydrogen and used fry oil)	7,532,347*	1,785,182	Gallons or equivalent
Electricity-Propulsion	713,575,016	779,942,081	Kilowatt-hours
Electricity-Battery	1,358,800	3,157,141	Kilowatt-hours

Note: Electricity-Propulsion refers to systems powered by electric rail or catenary type systems. *2015 data for "other fuels" appears to be erroneous (duplicates LPG data) [124]

Overall, as shown in above, transit systems account for only about 2% of overall fuel use in California [83]. However, transit systems provide critical transportation support services for disadvantaged communities (DACs) and others with disabilities and therefore provide a public good especially when operated efficiently. California is pursuing a strategy of zero-emission transit buses through its Innovative Clean Transit Rule to transition bus fleets to battery and fuel cell technologies by 2040 (see policy section) as well as encouraging greater use of transit and light rail. Greater use of these lower emission modes is an important part of the overall ability to get to carbon neutrality in the transportation sector in the next 25 years.

3.4.6 Transportation pricing strategies

There are a number of mechanisms by which transportation system pricing can be used to influence and potentially decrease per capita VMT. These include roadway and bridge tolls, high-occupancy toll (HOT) lanes, cordon pricing for vehicles entering inner city areas, and a variety of other measures including subsidized transit passes for low income citizens. Adverse impacts on lower income populations are clearly a concern with any type of pricing strategy. Key questions include the type of program and details of implementation, with possible means-based pricing/tolling strategies, as well as what is done with the revenues generated from the program. These details can greatly impact whether a pricing policy is regressive, neutral, or progressive from a social equity perspective. These and further environmental justice (EJ) issues are discussed in Section 1.8 below.

In a broad review of VMT reduction policy strategies, Boarnet and Handy [126] identify pricing strategies as leading options because they can be implemented and have effect relatively quickly, as well as impact a broad base of travelers. Pricing strategies also generate revenues that can be used for transportation enhancement projects as well as offsets for any regressive taxation impacts. Boarnet and Handy classify pricing policies into "link and cordon toll," "VMT fees," "fuel prices," and "parking pricing" categories. The effect sizes estimated from the literature for these categories are shown in Table 3.14 below.

Table 3.14. Pricing Policy Effect Estimates by Category [126]

Pricing Policy	Elasticity (unless otherwise noted)	Source
Link and Cordon Tolls	-0.1 to -0.45	ARB policy brief on road user pricing
VMT fees	-11% to -14.6% reduction from shifting gas tax to VMT fee	ARB brief on road user pricing, from Oregon VMT fee experiment
Fuel prices	-0.026 to -0.1 (short-run) -0.131 to -0.762 (long-run)	ARB brief on gas price
Parking pricing	-0.3 for demand for parking spaces	ARB parking pricing and parking management brief

Also in a recent white paper, Shaheen et al. [127] review seven types of pricing strategies: 1) cordon/area pricing, 2) distance-based pricing, 3) dynamic congestion pricing, 4) means-based pricing, 5) flat-rate tolls, 6) full-facility tolls, and 7) managed lanes. They note that various forms of pricing may be effective at reducing congestion and overall VMT while generating revenue for public agencies. For example, in London, Stockholm, and Singapore where cordon or area pricing has been implemented, the results have been successful with respect to congestion reduction [128]. Further details on the London, Stockholm, and some other regional pricing program experiences are included below.

An important finding from early implementation experiences is that pricing approaches may only be effective at reducing congestion if other transportation modes, including public transit and active transportation infrastructure, are available and accessible, as was the case with London, Stockholm, and Singapore [129] and [130] The pricing mechanism used, for example flat-rate or dynamic, will also influence the degree of effectiveness of the strategy. Dynamic pricing fluctuates with congestion, with the price of the toll rising with congestion. Thus, dynamic pricing is more effective at reducing peak period congestion, whereas flat-rate pricing is less effective since it does not incentivize drivers to change the time of day that they travel. In addition, not all pricing approaches produce the same equity outcomes. For example, if alternatives to driving are not readily available, roadway pricing can be a regressive tax on lower income who pay a higher relative percentage of their wages on transportation services than middle and higher income groups. The details of the equity impacts depend strongly on how the project revenues are then distributed. For example, revenues could be simply returned to regional general funds, or instead at least in some measure targeted to return to especially lower-served communities for transportation and jobs/work balance enhancement type projects.

An assessment of several roadway pricing or tolling projects in the U.S. and Europe, found that significant reductions of VMT were achieved in some of these program [131]. For example, in 2006-07 the state of Oregon performed a "Road User Fee Pilot Test" project to experiment with a road user based fee structure rather than a gasoline tax. This simulation was done in the Portland area where drivers were asked to behave as if they were paying the proposed tax, but did not actually have to pay it. The fees increased during peak times and in congested zones. Both overall VMT reductions (10-13%) and mode choice changes during the peak hours (away from driving and towards transit, especially for those living near transit stations) were observed. A similar study was conducted in the Puget Sound area with a sample of over 400 vehicles, and a hypothetical tolling and road charge scheme. The study found a 12% reduction in VMT and also decreases in average travel time from lower congestion, as was also observed in Oregon [132].

Another well-known project known as the “Stockholm Trial” was a cordon pricing program for Central Stockholm was started in 2006. The program demonstrated a reduction of traffic volume in inner Stockholm of 16% in the morning and 24% in afternoon/early evening, as well as a 14% reduction in VMT in the charging zone. Finally, in a well-known London cordon-pricing implementation, VMT reductions of 15% for four-wheel vehicles were reported after the first year of the initial Central London implementation in 2003-2004, and an 18% reduction in vehicles coming into the zone. The trips were instead made by transit (50-60%), diversion around the cordon zone (20-30%), and shifting to bicycle, motorcycle, or taxi (8-10%). A subsequent expansion of the project to a “Western Extension” around 2006 showed a 14% reduction in vehicle traffic and an 11% reduction in VMT among four-wheel vehicles [131].

Finally, with regard to broader transportation financing strategies, we note that the state of California has mechanisms by which it can use broader transportation financing regimes to influence MPO level efforts to emphasize VMT reduction. As state money flows from the state government to the MPOs to support regional transportation system enhancement projects, the state could require stronger regional efforts to reduce per - capita VMT as conditions for full funding [132]. These are already occurring in context of the currently required long-range Sustainable Community Strategies but without strong mechanisms for achieving specific desired outcomes. More specific policies such as VMT-based road fees, along with the recent shift to examining VMT impacts versus level of service for CEQA compliance, could help to deliver more reliable reductions in regional VMT. These could be combined with strategies for revenue return to lower income groups and for transportation improvements in local communities to avoid regressive taxation impacts on lower income groups.

3.4.7 Active transportation

Active transportation includes walking and bicycling. A 2018 Legislative Analyst’s Office Primer on California’s Transportation System, based on three national household travel surveys conducted between 2001 and 2017, found the following:

- 11–13% of all trips in California are walking trips, 2% higher than the national average. However, only 3% of workers commute by walking.
- Between 2001 and 2017, the share of bicycle trips in California increased slightly but still only represents 1% of trips. Only 1% of workers commute by bike.

Most of the existing literature focuses on the linkage between pedestrian/bicycle policy interventions and the use of the pedestrian/bicycle infrastructure; whereas, the linkage between active transport policy interventions and VMT is less well understood. Moreover, where evidence for notable increases in bicycling/walking use and decreases in VMT from bicycle/walking related policies exists, it is difficult to parse out the direct impact of individual policies (Winters et al. 2017) [133]. However, Winters et al. (2017) find that groups of policies that produce convenient, safe, and connected walking and biking infrastructure can notably promote active travel. Moreover, the study argues that comprehensive policy frameworks that incentivize active transport travel at a societal level, city level, route level, and individual level are necessary to achieve significant gains in active travel.

Scheepers et al. [93] review the literature related to the effectiveness of policies that aim to shift travelers from the personal vehicle to active transport modes. The study segments the policies/interventions into: work-place based interventions, architecture and urbanistic adjustments (i.e., the built environment), population-wide interventions, and bicycle renting system interventions. Their review of the literature claims that nearly all studies find a positive impact of a policy/policies on mode shift; however, the studies in the literature rarely present the statistical significance of their findings. Moreover, the authors claim that their review of the literature also finds that a combination of interventions is needed to promote active travel and reduce personal vehicle usage, rather than individual policies [134].

The Scheepers et al. review finds that while mass media campaigns appear to be beneficial when implemented alongside other interventions, the media campaign itself is neither a necessary nor sufficient condition for a mode shift from personal vehicle to active transport modes [134]. Regarding economic incentives and disincentives, the results highlighted in the review indicate that sustained incentives and disincentives can shift travelers to active transport from the personal car; however, when the incentives/disincentives expire, travelers tend to switch back to the personal vehicle.

Empirical results indicate that the benefits of bicycle and pedestrian infrastructure are most likely to accrue in metropolitan areas rather than rural areas [126]. Unfortunately, the VMT benefits of active transport infrastructure investments are typically minor as they only benefit travelers who live and complete activities within the geographical region of the infrastructure investment. Hence, the VMT reduction benefits of active transportation infrastructure investments are likely most beneficial alongside land use changes that result in higher density and higher diversity of activity types within cities. The increased density and diversity typically allows travelers to travel shorter distances, thereby, making active transport modes competitive with vehicle-based modes for these trips. Investments in active transportation infrastructure can help to provide pathways for higher density developments to be built, and then the infrastructure such as bike lanes and pedestrian paths can be more fully utilized over time.

In a relevant California study, Marshall and Garrick (2010), using data from 24 cities in California, find that increases in bike lane length increase the commute mode share proportion of bicycling [135]. Moreover, the study finds that interactions between the road network structure, and the connectivity of the road network, significantly influence the commute mode share of bicycling and walking in complex ways.

3.4.8 Truck/freight VMT

Truck traffic in California is unevenly distributed geographically. Southern California has significant travel by all classes of trucks. Medium and heavy-duty trucks also show significant travel through the Central Valley and other freight corridors (Figure 3.29, Figure 3.30, Figure 3.31).

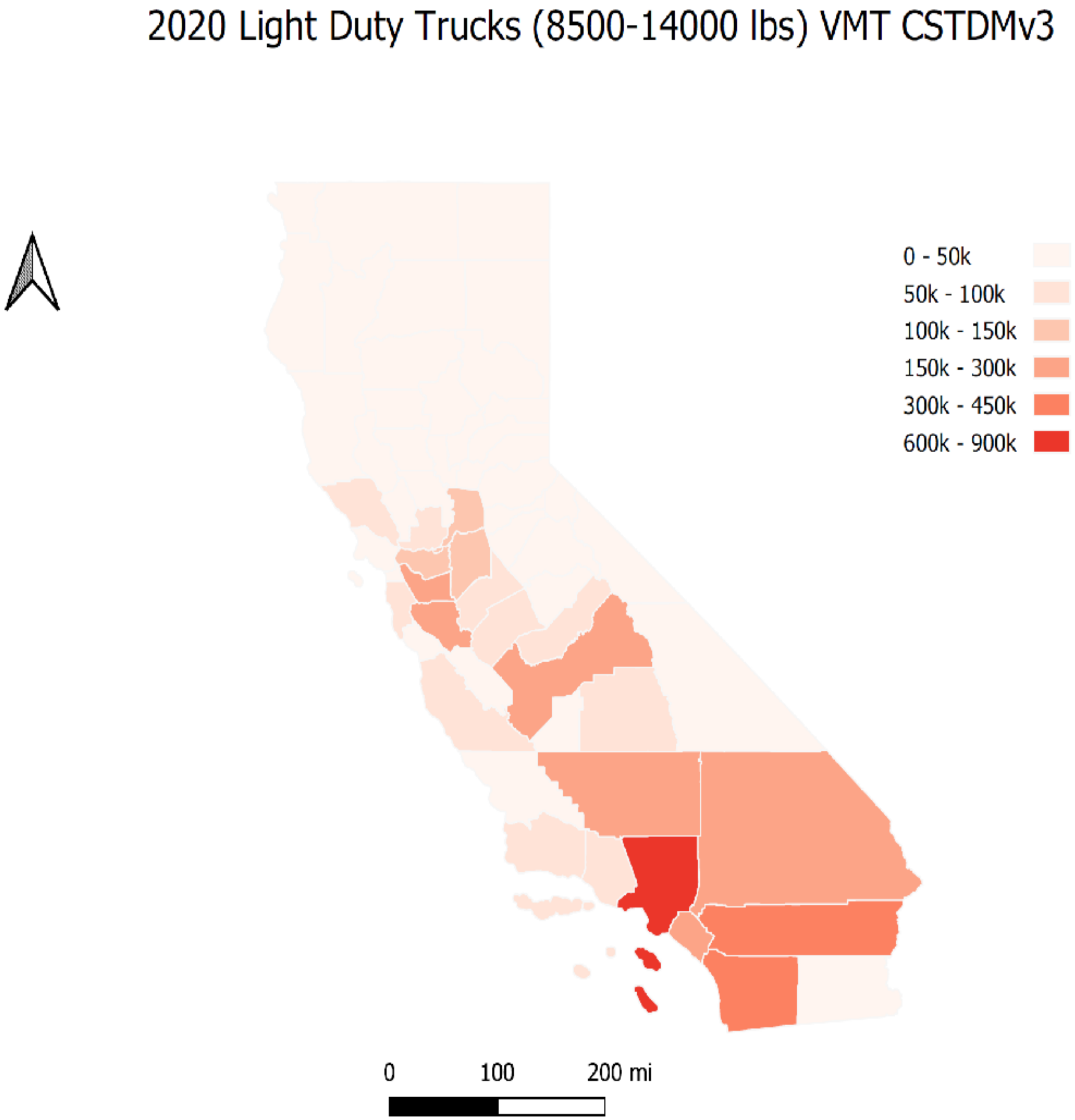


Figure 3.29. Daily VMT for Light Duty Trucks in California by county

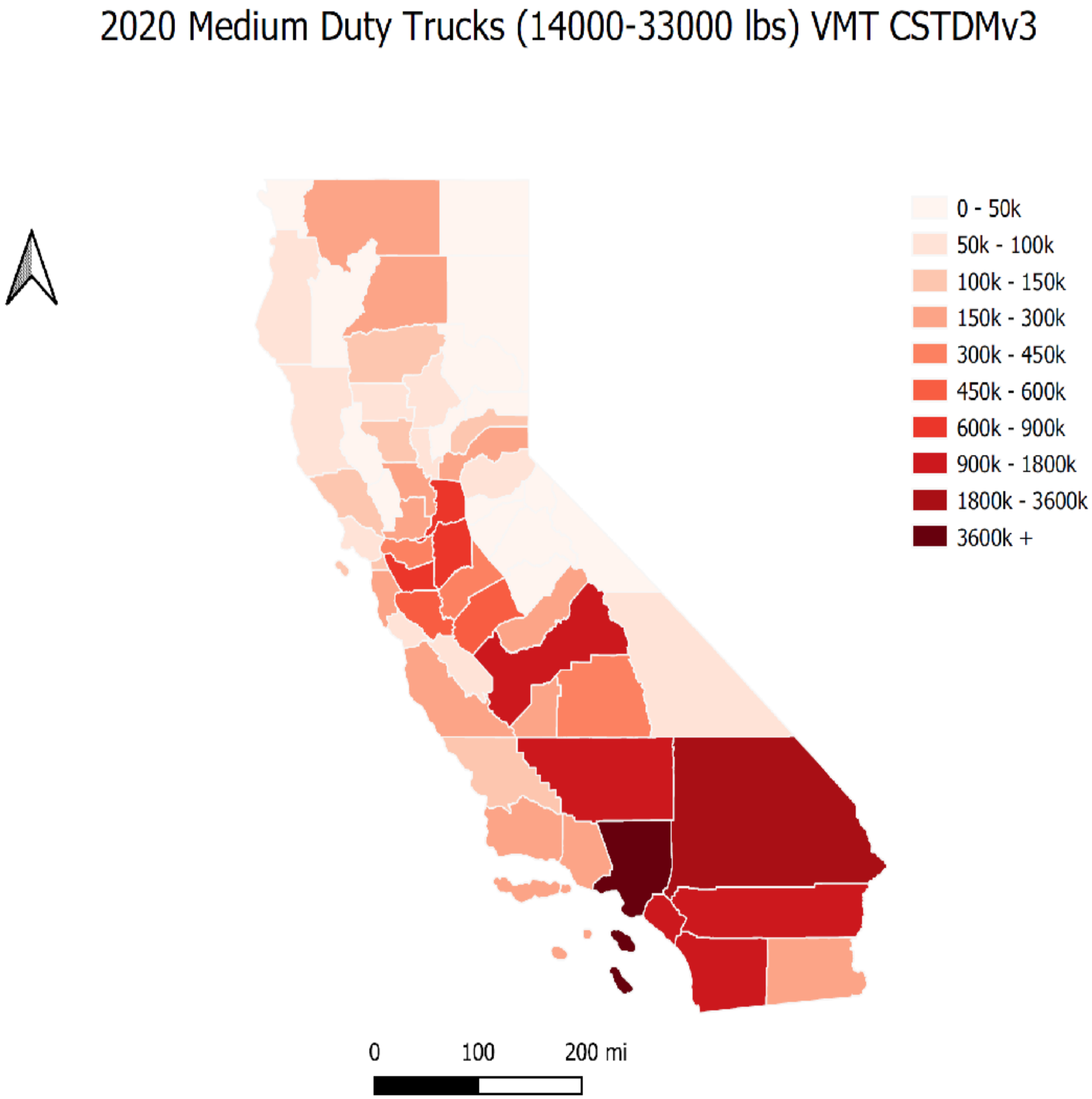


Figure 3.30. Daily VMT for Medium Duty Trucks in California by county

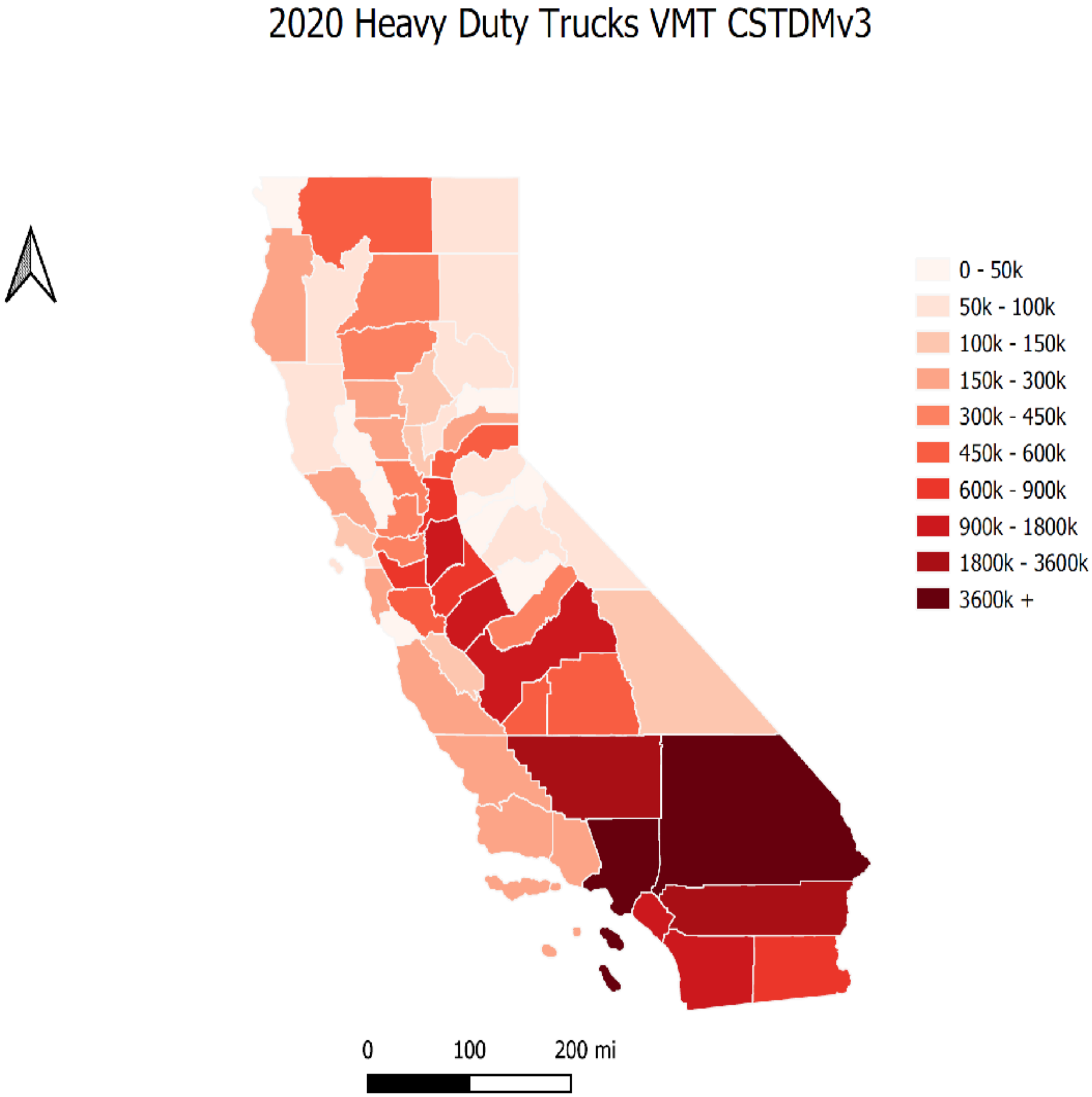


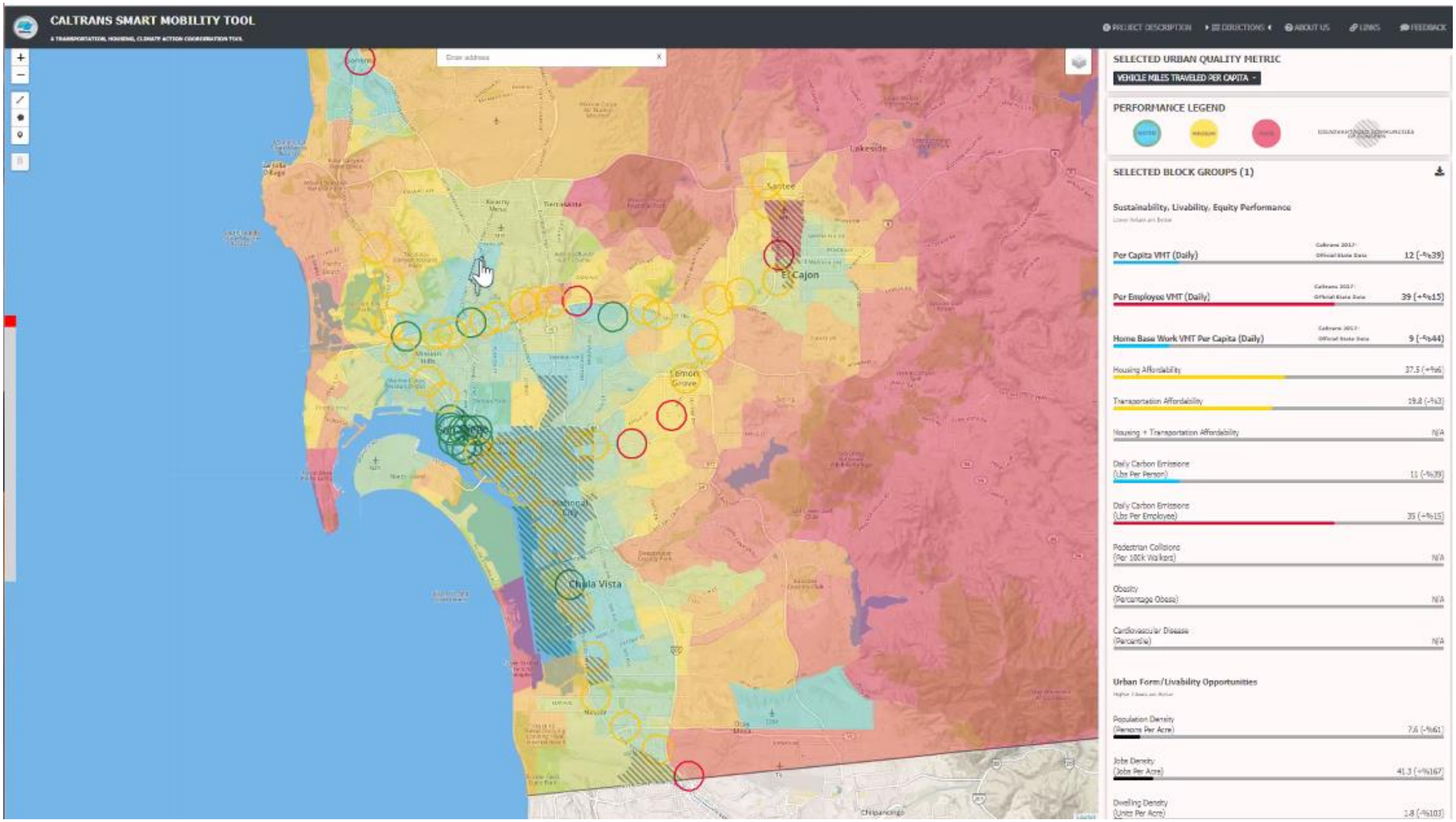
Figure 3.31. Daily VMT for Heavy Duty Trucks in California by county

3.4.9 Recent VMT Policy and Future VMT Policy Analysis Tools

The State of California Governor's Office of Planning and Research (OPR) is developing VMT analysis tools and resources based on the passage of SB 743 (Steinberg) [136]. SB 743 has shifted analysis of project level impacts under CEQA from level-of-service based impact analysis to a VMT-based analysis. This effectively amounts to a shift from managing congestion to a focus on managing and reducing VMT [137]. SB 743 took effect, statewide, on July 1, 2020.

Measures such as SB 743 that are more directed are needed to complement and help support the Sustainable Communities Strategy (SB 375) that encourages municipalities to consider strategies for VMT reduction in their planning, and requires them to identify plans for meeting GHG reduction targets. SB 743 allows for a shift in the focus to metrics much more closely tied to actual VMT levels and potential reductions, making them much more useful for assessing targets toward the state's environmental goals. This gives the state a better chance of success with its programs when combined with many other strategies for addressing VMT discussed above that include: land use and job/housing balances, enhanced transit system use, use of low-carbon intense new mobility, microtransit, and active mobility modes, and roadway and parking pricing strategies.

With regard to policy analysis tools for VMT reduction that have a spatial component, Professor Bruce Appleyard of San Diego State University, with support from Caltrans, has developed a tool called the Smart Mobility Tool that is now under beta release (https://testsmartgrowthcalculator.netlify.app/, Figure 3.32). This tool covers the several major urban areas of California. It groups local areas into eight different place types and provides a graphical depiction of key land use and transportation indicators by census tract, such as access to transit, carbon footprints, and commuter and home-based work travel along with overall per capita VMT. Model data files can be easily downloaded and then modified with the projected impact of specific policies, an analysis strategy that the project team is considering for further use in the project.



SELECTED URBAN QUALITY METRIC

VEHICLE MILES TRAVELED PER CAPITA

PERFORMANCE LEGEND

SELECTED BLOCK GROUPS (1)

Sustainability, Livability, Equity Performance

Per Capita VMT (Daily)	Caltrans 2017 · Official State Data	12 (-%39)
Per Employee VMT (Daily)	Caltrans 2017 · Official State Data	39 (+%15)
Home Base Work VMT Per Capita (Daily)	Caltrans 2017 · Official State Data	9 (-%44)
Housing Affordability		37.5 (+%6)
Transportation Affordability		19.8 (-%3)
Housing + Transportation Affordability		N/A
Daily Carbon Emissions (Lbs Per Person)		11 (-%39)
Daily Carbon Emissions (Lbs Per Employee)		35 (+%15)
Pedestrian Collisions (Per 100k Walkers)		N/A
Obesity (Percentage Obese)		N/A
Cardiovascular Disease (Percentile)		N/A

Urban Form/Livability Opportunities

Population Density (Persons Per Acre)	7.6 (-%61)
Jobs Density (Jobs Per Acre)	41.3 (+%167)
Dwelling Density (Units Per Acre)	1.8 (-%103)

Figure 3.32. Caltrans Smart Mobility Tool

3.5 Fuels

California depends primarily on gasoline and diesel refined from petroleum to power its transportation system. 84% of California's transportation energy is currently provided by petroleum, a value that is actually much lower than most other industrialized economies. For example, about 95% of total U.S. transportation energy is derived from petroleum, with the alternatives being mostly ethanol blended into gasoline, whereas California consumes a significant amount of biodiesel (BD), renewable diesel (RD), renewable natural gas (RNG) and other non-petroleum fuels. The majority of petroleum is consumed as gasoline, the dominant fuel for light-duty passenger and commercial vehicles. MDVs and HDVs predominantly rely on diesel fuel (Figure 3.33). An increasing amount of biofuels have been blended into California's fuel supply over the last decade.

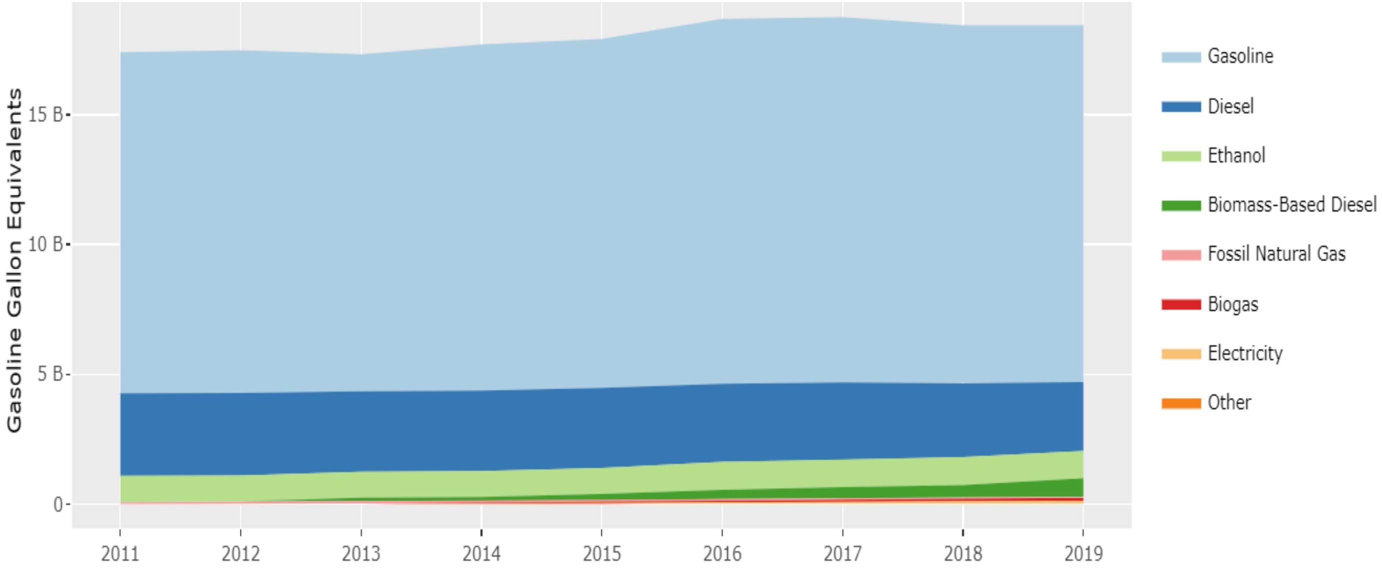


Figure 3.33. Transportation Fuel Consumption in California. The LCFS was largely responsible for creating and growing a market for biomass-based diesel substitutes, like BD and RD. They have become a significant contributor to California's fuel supply. Other fuels, like electricity, represent a small but growing share of the fuel market. Adapted from Smith, 2020 [138].

The first biofuel blended into transportation fuels at large scale was ethanol. The Federal Energy Independence and Security Act of 2007 expanded the use of ethanol as a substitute for gasoline, leading to a 10% ethanol blend (E10) becoming the default retail formulation in California and the rest of the United States. California's gasoline specifications differ from many other parts of the United States in that California has stricter requirements for fuel volatility as well as permissible levels of sulfur, aromatics, benzene and other harmful components. The petroleum fraction of California's retail gasoline is known as California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB). When mixed with ethanol, it yields a less-polluting formulation of gasoline called California Reformulated Gasoline (CaRFG) than what commonly used elsewhere in the country. California also has more stringent diesel standards, it was one of the first states to require ultra-low sulfur diesel, which reduces the formation of diesel particulate matter (PM) and enables the use of advanced diesel particulate filters to further reduce emissions. Additional standards set guidelines for aromatic hydrocarbon content and lubricity.

Since 2011, California's fuel consumption has stayed relatively stable, with some periods of modest growth. Demand declines in the aftermath of the 2008–2011 recession were counteracted by robust economic growth in the decade that followed. At present, California has a number of policies intended to reduce the consumption of petroleum, ranging from tailpipe GHG-emissions standards that support the deployment of more efficient vehicles to transportation demand policies like SB 375 [139], which requires metropolitan areas to reduce per-capita VMT over time. Despite these policies, aggregate travel in California has generally increased over time and has been only partially counteracted by vehicle-efficiency improvements, leading to a generally growing aggregate demand for fuel.

The supply of transportation fuels to California has undergone a significant shift since California's adoption of the LCFS. In order to meet the LCFS declining carbon intensity target, fuel suppliers must either reduce the carbon intensity of their products or buy credits from alternative-fuel producers. This directs a significant revenue stream from deficit-generating fuel providers (those selling petroleum gasoline and diesel) to alternative-fuel providers, while also creating an incentive for conventional fuel producers to help alternative fuels make it to market (since credits are only generated when fuels are actually used for transportation). Revenue generated from LCFS credits for electricity used as a transportation fuel are required to be reinvested in projects to further promote electrification in the transportation sector. Estimated total revenue for alternative-fuel producers under the LCFS has exceeded $6 billion since the program's inception (Figure 3.34)

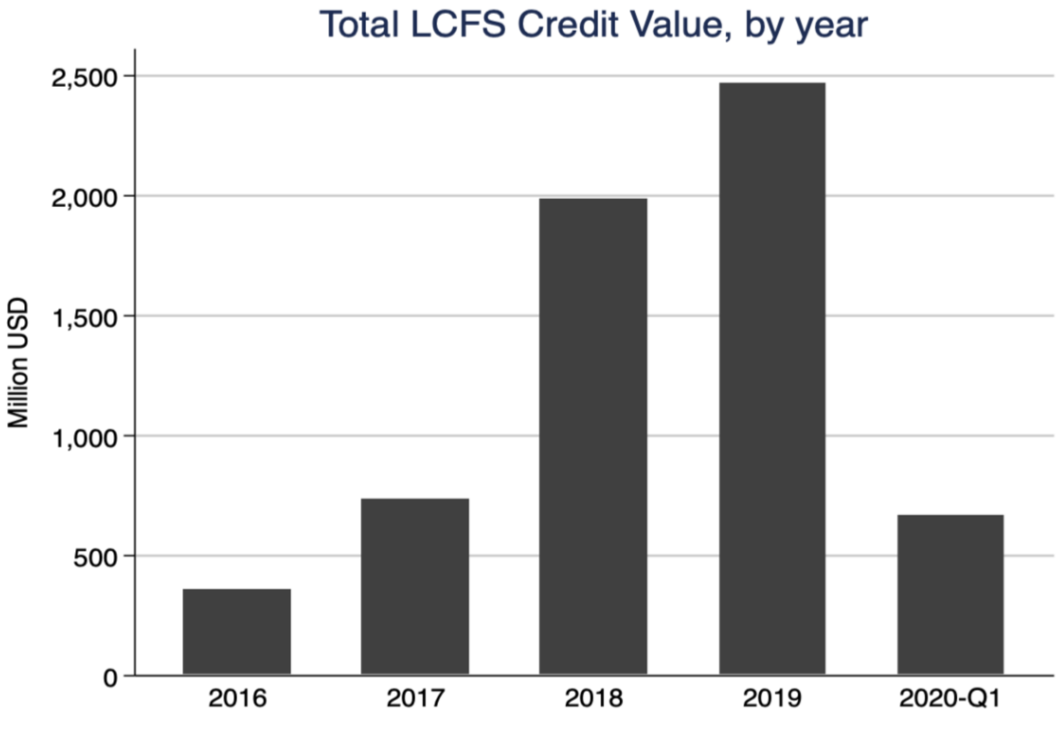


Figure 3.34. Total LCFS credit value 2016 through First Quarter of 2020. Credit values estimated by multiplying total yearly deficits by volume-weighted average price for the year [138].

LDVs in California are predominantly fueled by E10. The overwhelming majority of ethanol used in this blend is produced from corn, mostly grown in the Midwest and shipped to California by rail. When the LCFS was first adopted, most projections predicted that cellulosic ethanol would become a major compliance fuel under the program, delivering significant carbon reductions compared to corn. In practice, commercial-scale cellulosic ethanol has proved more difficult to produce than expected, due to challenges in procuring and handling feedstock at a low enough cost to be competitive, as well as difficulties overcoming inhibitory byproduct creation and scaling up the cellulosic production technologies to consistently produce viable commercial yields. Several early demonstration projects closed after cost overruns and under-performance. Many corn-ethanol producers have adopted cellulosic "add-on" modules designed to consume the cellulose in corn kernel fiber in order to increase ethanol yield; these modules typically add only 2–4% to the corn facility's yield.

In the long-term future (>10 years), electricity is likely to be the dominant alternative fuel in the LDV space, especially if critical decarbonization targets are to be met. At present, though, only around 750,000 plug-in vehicles are in use in California out of an LDV fleet of around 26 million [140]. Hence the impact of EVs on overall transportation-fuel consumption in California is relatively small at present, and will continue to be until the fleet expands further. Alternative fuels like biofuels, are therefore the predominant source of near-term emissions reductions and will continue to be for the next decade or more.

Since there are more cost-effective alternatives to diesel than gasoline at present, the gasoline pool in California has exhibited relatively minimal change since the inception of the LCFS. Ethanol remains the largest credit generator (Figure 3.35). As a whole, alternative fuels in the gasoline pool do not produce enough LCFS credits to offset deficits from petroleum-gasoline consumption. Gasoline producers instead purchase credits from diesel substitute producers to satisfy their LCFS obligations.

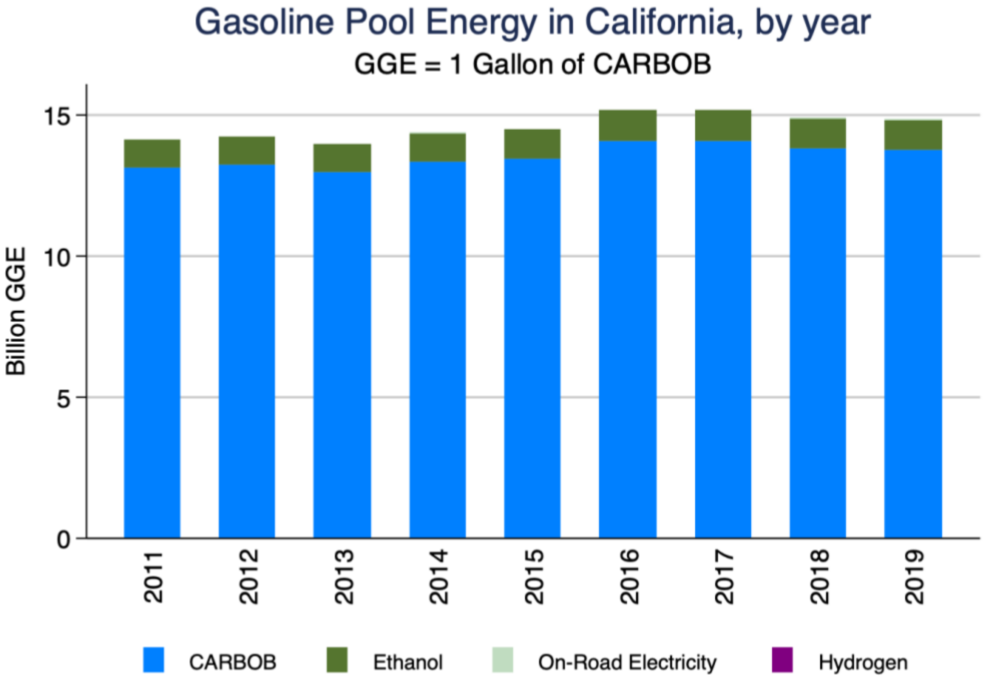


Figure 3.35. The gasoline pool has remained relatively stable year over year.

The diesel pool has seen a greater shift towards alternative fuels and a greater diversity of fuel options, due primarily to the more rapid commercialization of large-scale biomass based diesel fuels- BD and RD- than equivalents in the gasoline pool. Lower carbon diesel substitutes include:

3.5.1 Biodiesel (BD)

Biodiesel is made by esterification of from vegetable, animal or used food oils to yield Fatty Acid Methyl Esters, which are often abbreviated as FAME and used as another name for biodiesel. BD can be blended into conventional or RD at up to a 20% level without requiring modifications to engines or fuel systems. BD typically reduces total lifecycle GHG emissions by 30–60% relative to conventional diesel, depending on the feedstock used in BD production. BD also reduces formation of PM due to BD's lower sulfur content [141], and other chemical differences. In some older engines, BD may increase emissions of nitrogen oxides (NOx). CARB has issued a number of rules designed to mitigate this possibility. BD blends can sometimes suffer gelling or viscosity loss at cold temperatures, and so may require special handling and may not be suitable for all applications.

3.5.2 Renewable diesel (RD)

Renewable diesel is made by hydrotreating vegetable or waste food oils in a process similar to that of a petroleum refinery. The resulting fuel meets the technical specifications for conventional diesel fuel, most notably ASTM D975, which means that it can be burned in any diesel engine at any concentration without modification, making it a “drop-in” fuel, compatible with existing vehicles and fuel distribution infrastructure. RD typically achieves comparable or marginally higher lifecycle GHG emissions than BD, due to the more energy-intensive production process. RD also significantly reduces PM and slightly reduces NOx when substituted for petroleum diesel.

3.5.3 Natural Gas and Renewable Natural Gas (NG and RNG)

Several engine manufacturers have developed engines, aimed at the HDV market, that burn natural gas (NG). NG engines typically emit less PM than diesel-powered engines. Advanced, extremely low NO_x versions of NG engines have recently entered the market. NG engines running on fossil-fuel-based NG offer a 10-20% reduction in lifecycle GHG emissions relative to conventional diesel-powered engines; NG can burn cleaner than diesel, but there are often significant fugitive releases of methane associated with production and distribution of fossil-fuel-based NG. Natural gas engines also generally require spark-ignition engines instead of more efficient compression-ignition ones. Renewable natural gas (RNG) can be captured from decomposing organic matter and can offer significantly lower lifecycle GHG emissions. In some cases, RNG generation prevents the release of methane. This generates large additional GHG credits that can be applied to the fuel, resulting in RNG sources which have a negative assessed GHG value. This avoided methane credit is appropriate as long as other policies have not required mitigation of fugitive methane sources. In California, SB 1383 and the Short-Lived Climate Pollutant Reduction Strategy sets a target to achieve a 40% reduction in methane emissions by 2030. Anaerobic digesters are a likely option for compliance with organic waste disposal and manure management requirements of SB 1383 and a significant expansion of in-state RNG production from digesters is anticipated. Even with anticipated expansion, however the total supply of RNG from in-state sources is likely to be limited. Jaffe and Parker [142] evaluated potential in-state supply and found a maximum potential production around 82 billion standard cubic feet per year, equal to about 560 million diesel-equivalent gallons of fuel, however production under likely economic conditions would be lower. Depending on the reductions that can be achieved through incentives for voluntary mitigation, CARB anticipates that mandatory methane reduction requirements will be necessary to achieve the target. CARB has indicated that projects in place prior to the effective date of a mandatory methane reduction would still be eligible for avoided methane credit to reduce the carbon intensity of the resulting RNG under the LCFS for up to 10 years, while new projects implemented after such regulation takes effect would only be eligible for emission reductions that exceed the methane reduction requirements. This means that very low-carbon RNG, despite comparatively small volumes, could play a significant role in California's fuel pool through the early to mid-2030's.

3.5.4 Electricity

In addition to alternative fuels for combustion engines, electricity is taking on a larger role in the medium- and HDV sector. Electric motors offer a couple of advantages in medium- and heavy-duty applications, in addition to their much higher fundamental levels of efficiency. These advantages include high torque, the ability to reclaim energy from regenerative braking, and lower emissions in applications that often occur in proximity to workers or sensitive populations. Electric vehicles also provide a strong contribution to meeting state-wide emissions targets and offer an opportunity to be used as flexible demand or even electricity storage, when combined with appropriate grid upgrades. Electric motors also offer an opportunity to decarbonize the fuel supply for vehicles as the electric grid reduces its emissions, as well as the potential to integrate vehicle charging in grid-supportive patterns, which can help accommodate high levels of variable renewable energy on the grid.

3.5.5 Hydrogen

Hydrogen fuel cells offer an alternative to batteries for electric drive trains, so most of the advantages of an electric vehicle also apply to hydrogen ones. While the hydrogen fuel cell system ultimately produces electricity, hydrogen's chemical form enables seasonal energy storage; that is, using electrolysis to store excess electricity for later use. FCEVs also typically offer quicker refueling times than batteries and a superior energy density by mass than most battery types, though their energy density by volume tends to be lower than most batteries.

Petroleum diesel still comprises the majority of fuel in the MDV and HDV spaces, but alternatives have made significant inroads into this market. With a variety of diesel alternatives available, and numerous test and demonstration projects supported by federal, state, local, and philanthropic support, there has been a greater diversity of fuel types in the diesel pool than in the gasoline pool. There has also been a significantly higher rate of aggregate credit generation in the diesel pool, leading to a net flow of credits generated by diesel substitutes towards meeting compliance obligations arising from gasoline use. In particular, BD and RD have proved cost-effective and scalable under current technological and economic conditions (Figure 3.36).

3.5.6 Near-Term Fuel Outlook

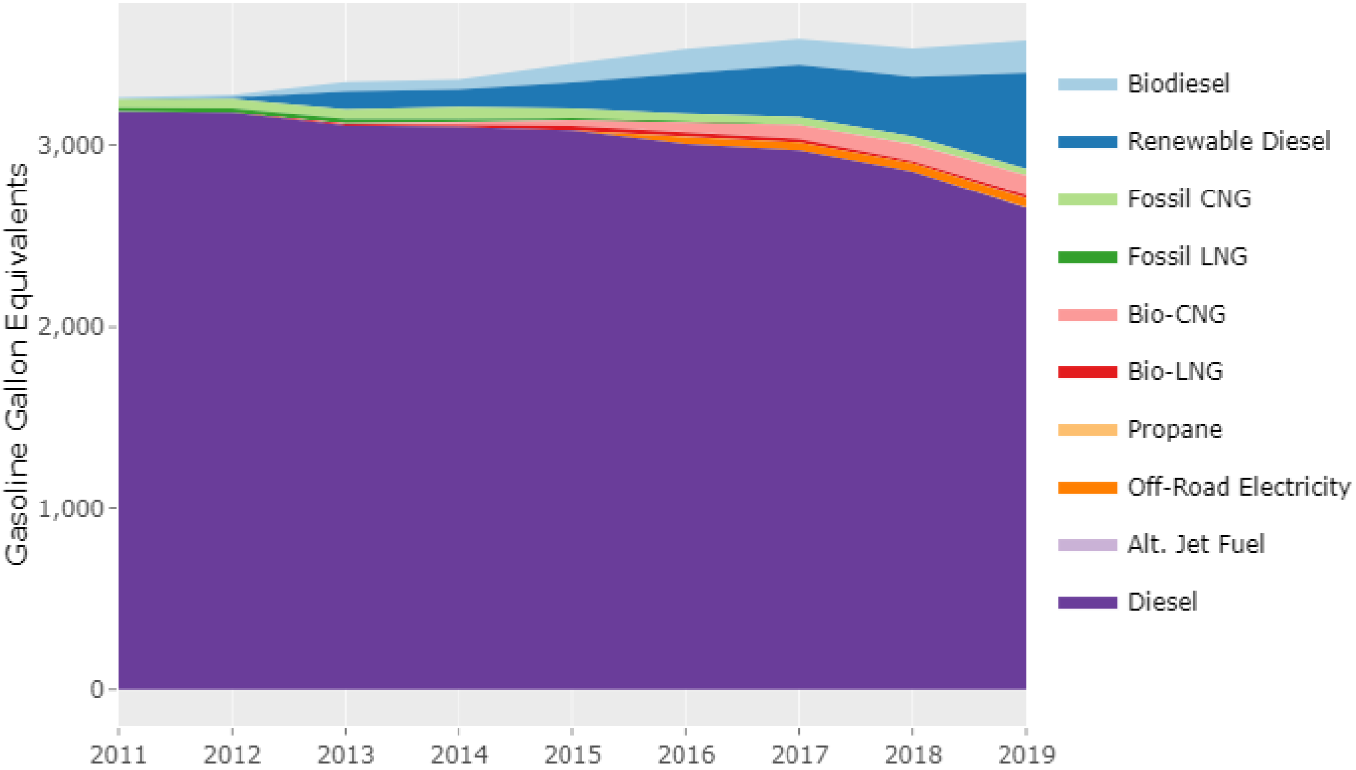


Figure 3.36. Diesel and Diesel Substitute Consumption in California. Under the LCFS Fuel use by MDV and HDVs has significantly shifted from almost entirely fossil-based to around one-sixth renewable over the last decade.

Overall, the LCFS has supported significant deployment of advanced, low-carbon fuel technology into the California market. While ethanol still dominates the total volume of non-petroleum fuels, it has been eclipsed as a credit-generation option by several diesel substitutes (Figure 3.37). The coming decade of fuel market evolution in California will likely continue this trend. Ethanol's contribution to the fuel pool, and to LCFS credit generation is likely limited by the "blend wall," the maximum amount of ethanol which can be blended into retail gasoline. There have been some preliminary steps taken towards lifting the blend wall, possibly to a 15% standard blend (E15), however significant barriers exist before it could be widely deployed. Absent a transition from an E10 to E15 standard, or a significant deployment of flex-fuel vehicles which can use up to 85% ethanol, there may be limited opportunities to increase the total amount of ethanol in the fuel pool. Deploying CCS at ethanol production facilities has been proposed as a method for reducing the carbon intensity of the resultant fuel, which could allow more LCFS credit generation and lower GHG emissions from the same volume of fuel [143]. Without either a higher blend wall or significant reductions in carbon intensity, ethanol will likely produce a significant but declining share of total compliance credit under the LCFS. BD and RD will likely continue to be the most important compliance fuels for the next several years. The growth potential of BD and RD may be limited by the availability of low-carbon feedstocks, such as waste oils from food processing, or may be augmented by the emergence of cellulosic technologies. Without the development of advanced technology and ample supplies of sustainable, low-carbon feedstock, biofuels will struggle to contribute to the attainment of California's long-term emissions goals.

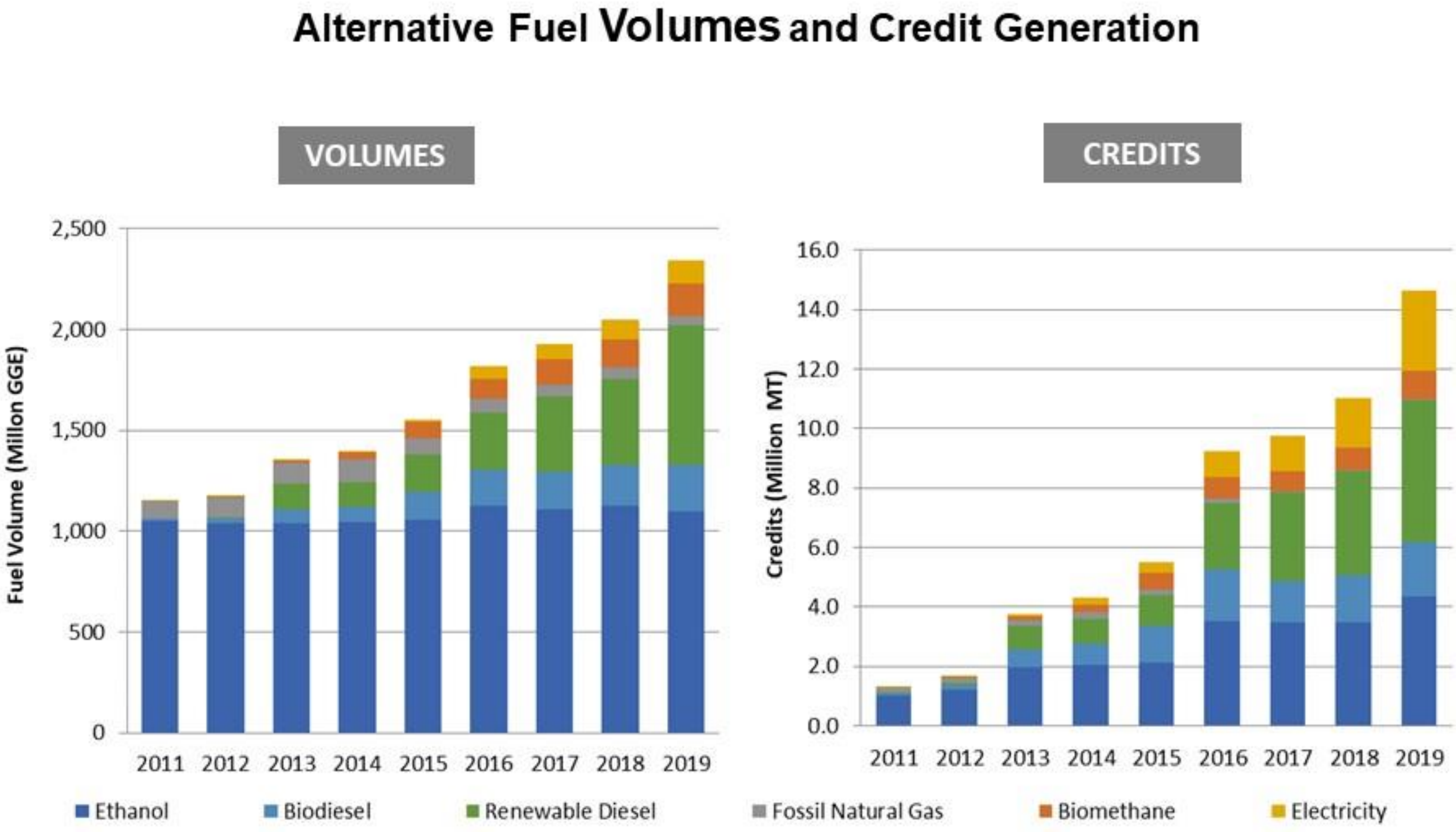
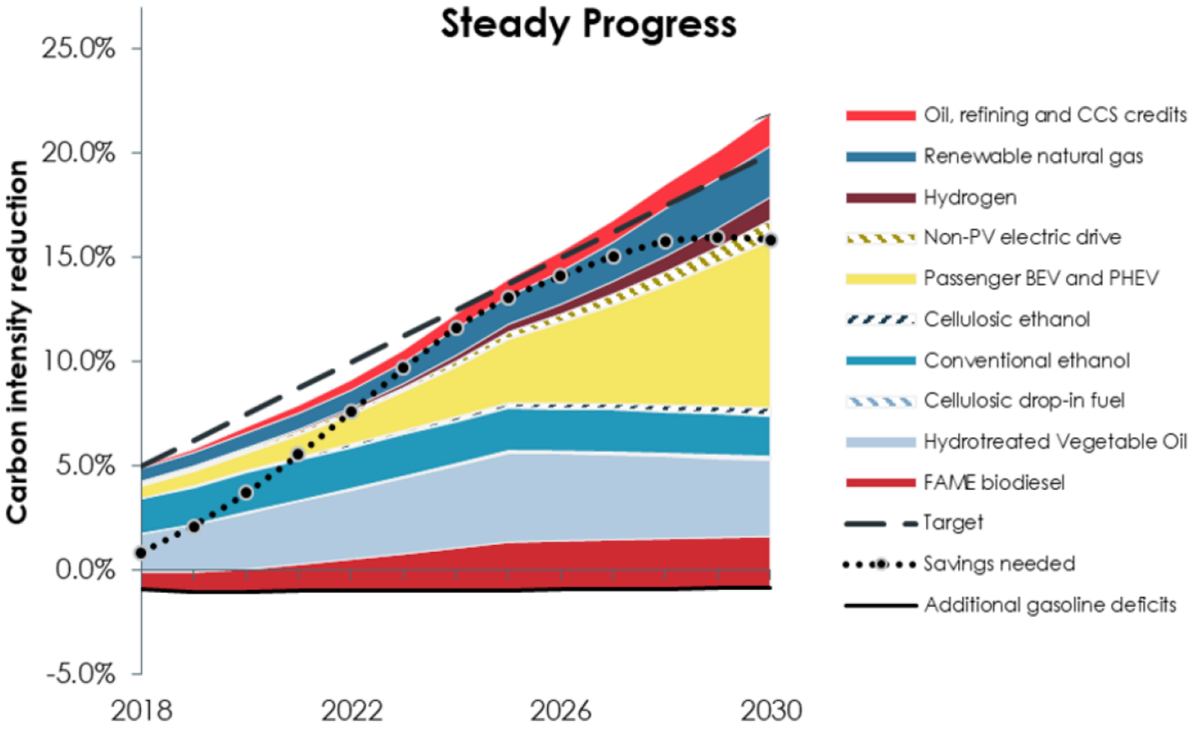


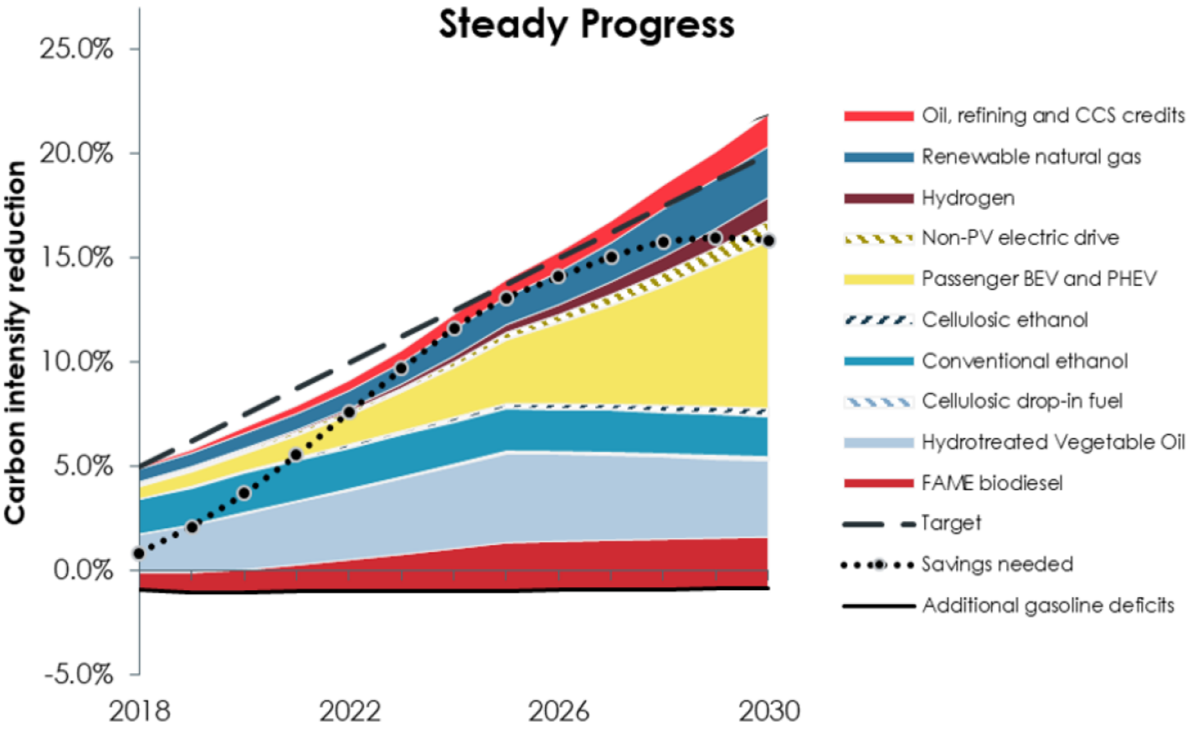
Figure 3.37. Fuel Volumes and LCFS Credit Generation by fuel. Ethanol dominates the volume of low-carbon fuels consumed but other fuels play a greater role in compliance with the LCFS.

The ability of the LCFS to meet its 20% carbon intensity reduction target by the end of this decade will likely depend on progress in deploying PEVs. PEVs serve as a significant credit generator while simultaneously displacing gasoline, the dominant generator of deficits. Few, if any other technologies, can provide zero or near-zero carbon transportation at the scale likely required to achieve a 2045 carbon neutrality target. But PEV technology should not be considered a silver bullet on its own. Barring an unexpectedly rapid advance in PEV technology, California will need to rely on diverse portfolio of solutions in order to meet its decarbonization targets in 2030 and beyond (Figure 3.39).



Source: California's Clean Fuel Future

Figure 3.38. Expected compliance with the LCFS by fuel



Source: California's Clean Fuel Future

Figure 3.39. Expected compliance with the LCFS by fuel

3.6 Equity and Environmental Justice

3.6.1 History and principles of environmental justice

The concept of Environmental Justice (EJ) originated as a response to the limitations of traditional environmentalism. Mainstream environmentalism successfully championed the efforts to protect, conserve, and replenish wildlife and wilderness, but did little to address the conditions in human-made environments. Environmental concerns not addressed by the environmentalism narrative included the inequitable distribution of environmental harms and benefits in minority communities, recognition of historical precedents that hindered DACs to secure cleaner environments, and a lack of outreach and engagement with groups in those historically disenfranchised communities burdened with adverse environmental conditions.

Post-war zoning codes and land use practices are viewed as the sponsors of the inequities that incited the EJ movement. These regulating mechanisms allowed for whites to secure newer, cleaner, and more prosperous environments while explicitly suppressing DACs to harmful, dangerous, and dirtier urban spaces. The right to clean and prosperous environments would eventually be absorbed as an element of the Civil Rights Movement. By the 1980s, the environmental justice framework had solidified and defined its purpose: the protection for all people regardless of race, color, nationality, or income from environmental and health hazards, and equal access to the healthy environments in which to live, learn, work, and play [144].

While the history of environmental justice dates back generations, many EJ advocates recognize the start of the modern EJ movement with the drafting and adoption of the 17 Principles of EJ established at the First National People of Color Environmental Leadership Summit held in Washington, D.C. in 1991 [108] (See Appendix).

The preamble to these principles attributed the existential threats to peoples and the land they live on to hundreds of years of colonization and oppression.[11] The 1991 Summit helped catalyze a series of Executive Orders issued by President Bill Clinton directing each federal agency to "make achieving environmental justice part of its mission by identifying and addressing, as appropriate, disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations," including tribal populations (Executive Order 12898) [145].

3.6.2 California's commitment to social equity

Due in large part to community advocacy spanning generations, in 2001 California became one of the first states to codify EJ in statute. California legislators have recently issued a suite of policies aimed at directing investment towards and providing protections for disadvantaged communities (DACs). These investments carry with them an explicit connection to EJ concerns. Notably, SB 535 (passed in 2012) channels proceeds from the state cap-and-trade program's Greenhouse Gas Reduction Fund (GGRF) to projects benefiting DACs. 2017's AB 1550 requires projects funded by the GGRF after that year to be located within (and directly benefit) DACs in order to count towards the 25% statutory investment minimums set by SB 535. Based on the 2020 California Climate Investment Legislative Report, 39% of the $2.6 billion of GGRF funds allocated since 2017 have gone towards projects directly located in and benefiting DACs.

California has established numerous additional policies and programs meant to address social and environmental disparities statewide. Many of these policies and programs rely on CalEnviroScreen, a GIS-based tool that identifies DACs based on a diverse suite of characteristics [146]. The product of multiple state agencies' collaboration with researchers and a broad array of stakeholders, CalEnviroScreen is currently in its third iteration and is housed at the California Office of Environmental Health Hazard Assessment (OEHHA).

In addition, California has made significant efforts in addressing the barriers limiting accessibility to clean transportation options for low-income, DAC, and tribal communities. SB 350 (De Leon, 2015) directed a series of reports that seek to identify and understand the challenges of such communities in securing clean transportation and mobility options. This resulted in pathways and implementation of programs targeting transportation equity by promoting active transportation, zero emission heavy-duty and light-duty vehicles, micro-mobility projects, and EV charging infrastructure funding in low-income, tribal and DAC

Furthermore, many state agencies now have formal advisory committees focused on equity issues, such as the California Air Resources Board, Environmental Justice Advisory Committee, the California Energy Commission and California Public Utilities Commission Disadvantaged Community Advisory Group, and the California Public

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[11] Indeed, the rise in civil unrest catalyzed by the May 2020 murder of George Floyd in Minneapolis grew in large part out of grievances directly related to this history of racialized colonization and oppression that contributed to the rise of the EJ movement as well as a reaction to EJ injustices themselves.

Utilities Commission Low-income Oversight Board. These groups represent diverse transportation and energy interests and allow for more inclusive policies to be developed to support social equity goals.

3.6.3 Transportation as an environmental justice issue

The EJ framework argues that low income and historically disadvantaged communities should not be burdened with environmentally adverse spaces. That in fact, low income communities and DACs have the right to spaces that promote health, safety, and prosperity. Therefore, a low-carbon transportation system to navigate those spaces in addition to the impacts and by-products of those modes are fundamental and should be considered in the EJ discourse.

The legacy of redlining, discriminatory lending practices, and racial covenants produced low income communities and DACs that were and continue to be burdened with poor quality of life, lack of public investment, and systematic oppression. Irresponsible zoning practices have sited polluting operations such as heavy industry and refineries in the vicinity of these same communities. To meet the demands of early suburbanization, many of these communities were often relegated as easily displaceable and bifurcated by transportation projects. Proximity to high emissions and toxins, coupled with disproportionate resource allocation, has resulted in range of adverse health conditions and few resources for mobility in low income communities and DACs.

Perhaps the most highlighted EJ concern in transportation in the disproportionate exposure to on-road particulate matter (PM). A 2019 study by the Union of Concerned Scientists (UCS) [147], found that in California exposure to PM from on-road sources (PM 2.5) is 10% higher than the state average in households with the lowest incomes. Additional findings indicate that African Americans and Latinos in California are on average exposed to more on-road PM than their white counterparts; 43% higher and 10% higher, respectively. This study also found that California households living without a personal vehicle are the most exposed to vehicle pollution, as they are likely to live in heavy-traffic urban areas. In other words, households that are least likely to have a car-dependent lifestyle, are most exposed and most burdened with the negative by-products of transportation (UCS, 2019) [147].

Energy operations for California's vast transportation sector have also impacted the local environment of DACs. Since the first comprehensive study in the U.S. on toxic facilities by the United Church of Christ (1987), findings indicate that polluting facilities are most likely to be situated in areas characterized with a high percentage of minorities [148]. This topic was revisited 20 years later (Bullard et al., 2008) [149] only to find presence of the same disproportionate allocation of oil refineries, gas power plants, and toxic waste disposal still disproportionately located in minority communities. Findings from a 2018 study (Mikati et al., 2018) [150] quantify the nationwide burden of PM to be 1.35 times higher in low-income communities than the overall population. Race continues to be a determining factor in exposure to PM, as the study finds particulate burden in non-whites to be 1.28 times higher.

High exposure to on-road pollution and pollutants emanating from toxic facilities have severe health implications. Cardiovascular diseases, respiratory problems, and premature deaths have all been linked to increased level of PM [151]. The high concentration of DACs near heavy traffic infrastructure and toxic facilities renders these communities as most vulnerable to these health hazards. According to the American Lung

Association, health threats from polluting environments are exacerbated in DACs as a direct result of their lower social and economic standing. Lack of access to proper health care, grocery stores, poorer job opportunities, dilapidated housing, and harsher work conditions are factors that intensify adverse health conditions and increases the risk of harm.

Access to transportation resources has the potential to significantly increase quality of life and opportunities for life choices. However, the cost of vehicle ownership, maintenance and insurance, public transit fares, and ride hailing fees, can hinder mobility for those with limited financial resources. While on average households in the U.S. spend around 20% of their income on transportation, the burden on low-income households can be as high as 30% of their income.

The number of communities that can be considered affordable dramatically decreases when the definition of affordability also incorporates social, economic, and environmental cost especially for overburdened communities. Low-income minorities coping with rising housing prices are forced to lower-cost housing, often located at a distance from employment hubs in central urban cores. This further impacts their social and economic standing, impedes access to critical services such as health care and grocery stores, and reduces proximity to economic opportunity and higher wage employment opportunities. In addition to these social, economic, and environmental costs, there are significant transportation-related costs. As a consequence of these housing and other land use implications, low-income individuals typically travel longer distances out of necessity, thus increasing their own cost burden of transportation. Unfortunately, the sprawling nature of cities in California makes it difficult for them to be adequately served by mass transit.

Race also plays a crucial role regarding the travel choices an individual makes and the modes they use. Over-policing in DACs has created an environment of fear and anxiety that discourages mobility via driving, bicycling, or walking for daily routine tasks. Consequently, low-income minority communities are further obstructed from accessing crucial resources that can provide a venue for social mobility and equally placing increased pressure on the need to transform the transportation system.

Sustainability for a future low-carbon transportation system will require active efforts to ensure that EJ concerns are addressed. A sustainable low-carbon transportation system should seek to minimize the environmental burdens and health implications on low income communities and DACs. Most importantly, a truly sustainable system should seek to extend the benefits of low-carbon transportation to low income communities and DACs in California in a manner which galvanizes social reform, by increasing connectivity for crucial life opportunities such as heath, employment, and education. Developing a sustainable low-carbon transportation system will require active efforts now.

3.6.4 Equity and environmental justice coordination

In this study, the researchers responsible for incorporating an equity lens and an EJ perspective worked collaboratively with the other research teams to examine the topics concerned with labor and employment, and health. The respective leads of the health and the labor and employment research teams both have a strong grasp of and commitment to equity and EJ. The equity and EJ research team also served an advisory role on technical aspects of this study, including to those teams researching heavy-duty and LDVs, VMT, and fuels. Collectively, these research teams worked in an iterative fashion with both state agency representatives working on EJ, as well as civic and community stakeholders statewide who advocate for the elevation and implementation of EJ principles into state policies. The research teams and equity and EJ team are committed to maintaining a high degree of accountability for the public and stakeholders. All parties worked in partnership to provide a space that allowed for input, feedback, and comments on best practices for dissemination of results. By taking these measures, the research team sought to ensure the clarity and transparency of the research conducted.

Understanding the transportation needs and perspectives of residents and stakeholders in DACs is critical to moving towards a more just transportation system. By connecting people from the most vulnerable communities to key life opportunities, transportation can serve as a cornerstone piece to increasing quality of life. The perspectives of residents and stakeholders in low income communities and DACs were also critical to guiding and informing this report and the policy and implementation impacts. This working group engaged with organizations that had previously developed relationships with state agencies and made significant strides forward in advocating and empowering EJ communities. These efforts were guided by CalEPA guidelines prioritizing equity, health, environment, resilience and adaptation, high road jobs, affordability and access, and minimizing impacts beyond our borders. This group coordinated efforts with and supported community engagement activities by the Health and Labor and Employment working groups.

This working group's approach involved outreach to the following groups, inviting them to provide input:

- Transportation Equity and Environmental Justice Advisory Group (TEEJAG) coordinated by the Center for Regional Change at UC Davis
- Community Air Protection Program Consultation Group coordinated by CARB
- Disadvantaged Communities Advisory Group (DACAG) coordinated by the CEC and the California Public Utilities Commission (CPUC)
- Last Chance Alliance, a coalition of advocacy groups

3.7 Health

3.7.1 Current state of local pollutants, health impacts

On-road motor vehicles (cars, trucks, and buses) generate air pollutants throughout their lifecycles (vehicle and fuel production, vehicle operation, and end-of-life). These pollutants endanger public health, especially for vulnerable groups, including children, low income groups, and DACs. The main pollutants from the operation of motor vehicles powered by ICEs include [152][153]: particulate matter (PM), carcinogenic volatile organic compounds, nitrogen oxides, ground-level ozone, carbon monoxide, and sulfur dioxide. Some of these pollutants are directly emitted from vehicles, and others are the result of chemical reactions in the atmosphere (e.g., secondary PM).

Particulate matter (PM). Airborne PM is a complex mixture of solid particles and/or liquid droplets ranging in size from 0.01 μm to more than 10 μm.[12] It is common to distinguish between coarse ($PM_{10-2.5}$), fine ($PM_{2.5}$), and

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[12] PM_x denotes particles with a diameter under x micron (10^{-6} meters).

ultrafine ($PM_{0.1}$ or UFP). More specifically, the US EPA defines $PM_{2.5}$ as particles collected by a sampler with an upper 50% cut-point of 2.5 µm aerodynamic diameter and a specific, sharp penetration curve as defined in 40 CFR Part 58 [154]. Ultrafine particles (UFP) are particles with a diameter of <0.1 µm based on physical size, thermal diffusivity, or electrical mobility [154].

PM is composed of both primary and secondary components. Primary PM comes directly from the operation of internal combustion engines as well as other anthropogenic and natural activities. Secondary PM are produced by atmospheric chemical reactions, including the oxidation of precursor gases such as SO_2 and NO_x to acids, followed by neutralization with ammonia, and partial oxidation of its organic components. The characteristics of PM mixtures depend on their sources, chemical composition, transport characteristics, atmospheric lifetime, and removal processes.

Because of their size, PM components can penetrate deep into the lungs and enter the bloodstream. The available scientific evidence shows that short-term (typically from a few hours to within one week), moderate-term (over one week to one month) and long-term (over one month) exposure to $PM_{2.5}$ can have a wide range of health impacts, ranging from inflammation of the airways and lungs to chronic inflammation, increased risks of heart, lung, and neurological diseases, premature mortality, and adverse pregnancy outcomes [154]. It is understood that there is no safe threshold under which exposure to ambient PM has no adverse health effects (WHO, 2006) [155]. Although the largest health impact of PM comes from long-term exposure to $PM_{2.5}$ or UFP, short-term exposure to high enough concentrations of PM can also exacerbate lung and heart conditions, strongly affect quality of life (including mental health), increase hospital and emergency department admissions, and contribute to premature deaths. Children, the elderly and those with pre-existing cardiovascular disease and respiratory disease (such as asthma) are particularly at risk. Evidence of the adverse health impacts of $PM_{10-2.5}$ is growing, particularly for respiratory health effects, but there are still some uncertainties [154]. There is also increasing evidence of association between exposure to ambient UFPs and a range of health effects (including respiratory and cardiovascular effects, as well as mortality), but understanding this linkage and eliciting causality effects are complicated by the difficulty of consistently measuring ambient UFP concentrations [154].

As of 2019, large areas in California were not in attainment with the national annual ambient standard for $PM_{2.5}$ (12.0 and 15 $\mu g/m^3$ for the annual arithmetic mean averaged over 3 years for primary and secondary $PM_{2.5}$; see US EPA, 2020) [156], including the San Joaquin Valley, most of the Bay Area, and counties in the Los Angeles South Coast Air Basin (US EPA, 2020) [156]. The annual California Ambient Air Quality Standard is 20 $\mu g/m^3$ PM_{10}, while there is no annual NAAQS for PM_{10}.

Some of the resulting health effects of PM on Californians have been documented in a number of studies [157]–[163], including for vulnerable groups. Children are especially at risk for air pollution because they have immature lungs, they tend to spend more time outdoors, and they often have higher breathing rates than adults. For example, Ostro et al. (2009) reported that components of $PM_{2.5}$ are associated with hospitalization for children for respiratory diseases such as asthma, bronchitis, and pneumonia. A number of other effects of exposure to fine particulate matter have been documented in the literature, such as preterm birth and low birth weight (e.g., see the meta-analysis of Li et al., 2017 [164] as well as Sheridan et al 2019 [165]; Basu et al 2014, 2017 [166], [167]) and stillbirth (Ebisu et al 2018 [168]).

$PM_{2.5}$ has also been found to be a major cause of environmental health inequality in the US, and in California in particular [169]. In a recent analysis of socio-economic and health characteristics at the census tract level, Liévanos (2019) [170] reported that the percentages of Latinx, non-Latinx Black, and non-Latinx Asian populations in census tracts are strongly and positively correlated with $PM_{2.5}$ percentile rankings, which shows that minority populations not only reside in areas with higher levels of $PM_{2.5}$, but they are also disproportionately affected by $PM_{2.5}$ air pollution.

Overall, CARB estimates that gasoline combustion was responsible in 2012 for 8% to 21% of $PM_{2.5}$ concentrations depending on the air basin considered [171]. Compared to gasoline exhaust, diesel exhaust is characterized by a substantially larger rate of PM release, on an equivalent fuel energy basis. Diesel PM consists mostly of carbon particles (~90% of which have a diameter under 1 μm) coated with organic and inorganic substances. The latter consists of soluble organic compounds, a number of which have been found to be potent mutagens and carcinogens [172]. Lowering the current annual $PM_{2.5}$ standard of 12 $\mu g/m^3$ to between 8 and 10 $\mu g/m^3$ could prevent as many as 4,600 annual premature deaths, 850 heart and lung disease hospitalizations, and 2,100 asthma emergency room visits in California (CARB, 2018) [171].

Volatile organic compounds (VOCs). VOCs are organic compounds that have high vapor pressure at ordinary ambient temperatures. Gasoline sources emit over 350 volatile organic compounds, including the toxicants toluene, m-xylene, propylene, benzene, n-hexane, formaldehyde, ethylbenzene, isobutene, 1,2,4-trimethylbenzene, and 1,3-butadiene. These are the most highly emitted VOCs from gasoline sources, along with acetaldehyde and propionaldehyde, that are known for their potential toxicity [171].

Significant sources of VOCs include chemical plants, gasoline stations, oil-based paints, autobody shops, and print shops. Emissions of gasoline-related VOCs with the most significant health concerns have been declining in California over the past two decades [171].

VOCs from gasoline-related sources can react with nitrogen oxides in the presence of sunlight to generate ozone, a key ingredient of smog. Reactions with other chemicals in the atmosphere can also produce a range of potentially toxic compounds, such as carbonyls, dicarbonyls, peroxynitrates (e.g., PAN, which are powerful respiratory and eye irritants, and are often present in smog), and phenols [171].

Short-term exposure to VOCs from internal combustion engines may irritate the eyes and the respiratory tract, increase the risk of asthma, cause headaches and nausea, and trigger visual disorders and memory problems. Long-term exposure to VOCs may also cause fatigue, damage the liver, kidneys, and central nervous system, cause birth defects and cancer [171], [173], [174]. Recent research has shown increased cancer sensitivity in children from early life exposure [174]. Although the cancer risk attributable to some of the most common carcinogenic VOCs emitted by gasoline has been dropping over the last two decades in California, some of the cancer risks for these substances still exceeded 1 in 1 million in 2014, and the cancer risks of a number of other gasoline-related VOCs are still unknown [171].

Nitrogen oxides (NO_x). Nitrogen oxides designate a group of seven gases, the two most common and hazardous are nitric oxide and nitrogen dioxide. NO_x results mostly from high temperature combustion. Substantial sources of NO_x include motor vehicle exhaust, the combustion of coal, oil, diesel, and natural gas (especially from electric power plants), industrial furnaces, and boilers. NO_x contributes to the formation of ground-level ozone and secondary PM (see above).

In recent years, NO_x concentrations throughout California have been below state and national ambient air quality standards except for a small area in Southern California along Highway Route 60 [175].

NO_x has direct and indirect effects on health. Short term exposure can irritate the respiratory system (also the eyes and the skin), aggravate respiratory diseases including asthma, and cause nausea, headaches, and abdominal pain. Long-term exposure to NO_x can, at low levels, cause asthma and respiratory infection, and at high levels impact female fertility, lead to genetic mutations, and even cause death [176]. Despite declines in ambient concentrations, NO_x levels are still of concern for health in California [157], [177], [178], particularly in the non-attainment area in Southern California.

According to CARB, gasoline-attributable fractions for NOx ranged in 2012 from 14% in the San Joaquin Valley Air Basin to approximately 30% in the South Coast Air Basin [179].

Ozone (O_3). Ozone is a highly reactive gas, which can be generated by natural or anthropogenic processes. It occurs both in the Earth's upper atmosphere (the stratosphere) and in the lower level of the atmosphere (the troposphere). While stratospheric ozone is formed naturally through interactions between UV radiation and oxygen, ground-level ozone is formed via photochemical reactions between a number of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) [180]. Pollutants leading to the formation of ground-level ozone are emitted from many sources including motor vehicles, various industries, fossil fuels, paints, and a number of consumer products [181].

Ozone is a key contributor to photochemical smog (or haze). Ground-level ozone can damage a wide range of materials, such as rubber, plastics, fabrics, paints, and metals. It can also damage sensitive vegetation and ecosystems, especially during the growing season, by reducing photosynthesis, impairing plant growth, damaging leaf cells, and making plants more susceptible to disease and insect damage.

Breathing ground-level ozone can have a number of adverse health effects, including inflammation of the airways, leading to coughing, throat irritation, chest discomfort, wheezing, and shortness of breath. Moreover, exposure to higher daily ozone concentrations have been shown to be associated with asthma attacks, increased hospital admissions, and in the most severe cases (older adults are more at risk), premature death [182]. Indeed, there is increasing evidence that long-term exposure to ozone can increase stillbirth, as well as respiratory and cardiorespiratory premature mortality [155], although available evidence is not as strong for the latter. Research shows that people who spend more time exercising outdoors are at greater risk from ozone exposure. In addition to people with asthma symptoms, children are especially at risk because they spend more time outdoors, tend to engage in more vigorous activities than adults, and inhale more air pollution than adults as a fraction of their weight [181].

Most of California is in non-attainment for both the 2015 and the 2008 8-hour ozone concentration federal standards [183]. Under the 2015 8-hour standard, the NAAQS for ozone is 0.070 ppm (down from 0.075 ppm in the 2008 primary and secondary standards), calculated as the fourth-highest daily max 8-hour concentration averaged over 3 years [184]. Ozone pollution is particularly severe in the Los Angeles-South Coast Air Basin and in the San Joaquin Valley [185]. The fraction of ambient ozone concentrations attributable to motor vehicles is currently not known precisely but it is thought to be substantial.

Carbon monoxide (CO). Carbon monoxide is a colorless, odorless toxic gas. The incomplete combustion fuels such as gasoline, natural gas, or wood generates carbon monoxide. CO can also be generated via photochemical reactions in the atmosphere from methane and non-methane hydrocarbons, other VOCs, and organic molecules in surface waters and soils [186]. Although CO can be emitted by a variety of sources, such as motor vehicles, power plants, incinerators, and wildfires, most atmospheric emissions of CO come from mobile sources.

Breathing air with high CO concentrations reduces the amount of oxygen that can be transported in the bloodstream, causing dizziness, confusion, fatigue, vomiting, and (at higher concentrations) death. Short-term exposure to CO for people with cardiovascular disease can further reduce their ability to respond to the increased oxygen demands of exercise or stress; inadequate oxygen delivery to the heart may lead to chest pain and decreased exercise tolerance. Overall, unborn babies (whose mothers are exposed to high levels of CO during pregnancy), infants, elderly people, and people with chronic heart disease, anemia, or respiratory problems are most at risk from exposure to elevated levels of CO [187].

There are currently no areas in California classified out of attainment with the California Ambient Air Quality Standards (20 ppm for the 1-hour average and 9 ppm for the 8-hour average).

We also note that CO contributes indirectly to climate change because it participates in chemical reactions in the atmosphere that produce ozone, which is a greenhouse gas. CO also has a weak direct effect on climate. For these reasons, CO is classified as a short-lived climate forcing agent. As a result, reducing CO emissions is considered a possible strategy to mitigate the effects of global climate change [186].

Sulfur dioxide (SO_2). Sulfur dioxide is a gas at ambient temperatures, which has a pungent, irritating odor. SO_2 is the most prevalent member of the sulfur oxides (SO_x) family in the atmosphere, and the one of concern for human exposure.

SO_2 results from burning fuels that contain sulfur. Common sources include motor vehicles (especially those with diesel engines), locomotives, ships, industrial processes (such as natural gas and petroleum extraction), oil refining, and metal processing.

SO_2 can react in the atmosphere to form PM, and thus reduce visibility by creating a haze. SO_2 also contributes to soil and surface water acidification and acid rain. This acidification harms susceptible aquatic and terrestrial ecosystems. In particular, acidification slows down growth and injures trees, and it can locally cause the extinction of various aquatic species. Moreover, SO_2 deposition promotes chemical reactions that facilitate the accumulation of mercury in water and soil, increasing the risks linked to mercury ingestion in human populations.

Exposure to SO_2 can impair breathing and exacerbate asthma. People with asthma, especially children, are particularly at risk [188].

There are currently no areas in California classified out of attainment with the national or the California Ambient Air Quality Standards (The 1-hour and 24-hour averages for the California AAQS are 0.25 ppm and 0.04 ppm respectively).

A look at (Figure 3.40, Figure 3.41, Figure 3.42, and Figure 3.43; data extracted from EMFAC 2017 [57]) shows that while PM_x and NO_x emissions from transportation decreased substantially over the last decade, both SO_x and CO_2 emissions have been increasing.

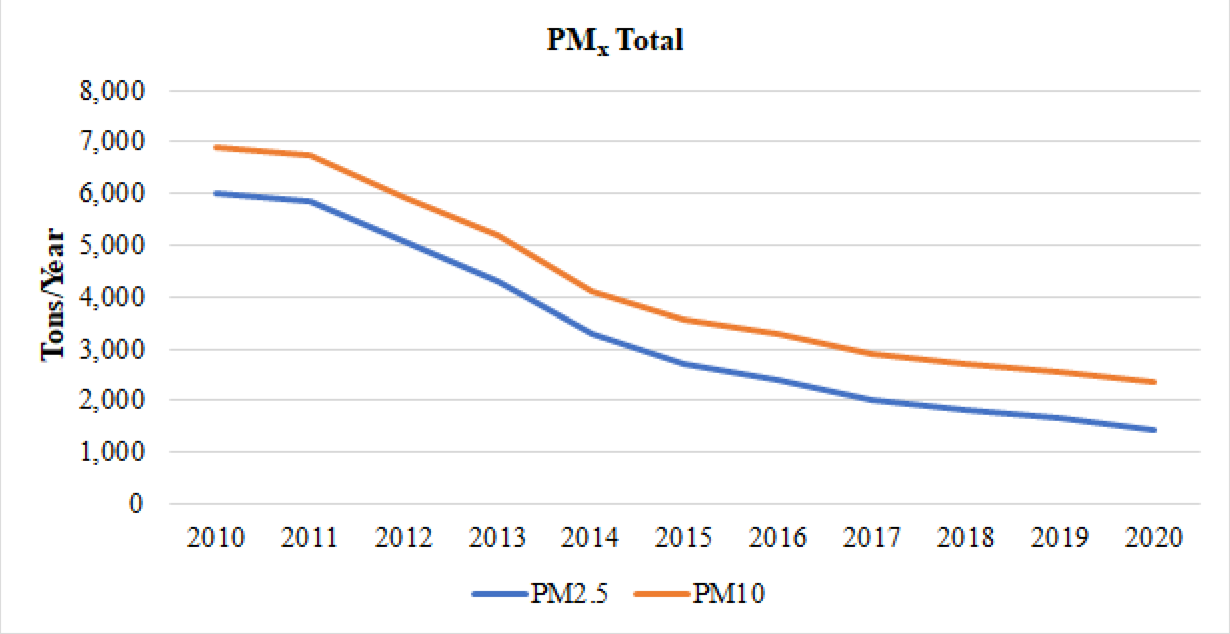


Figure 3.40. Evolution of total annual PM emissions from transportation in California

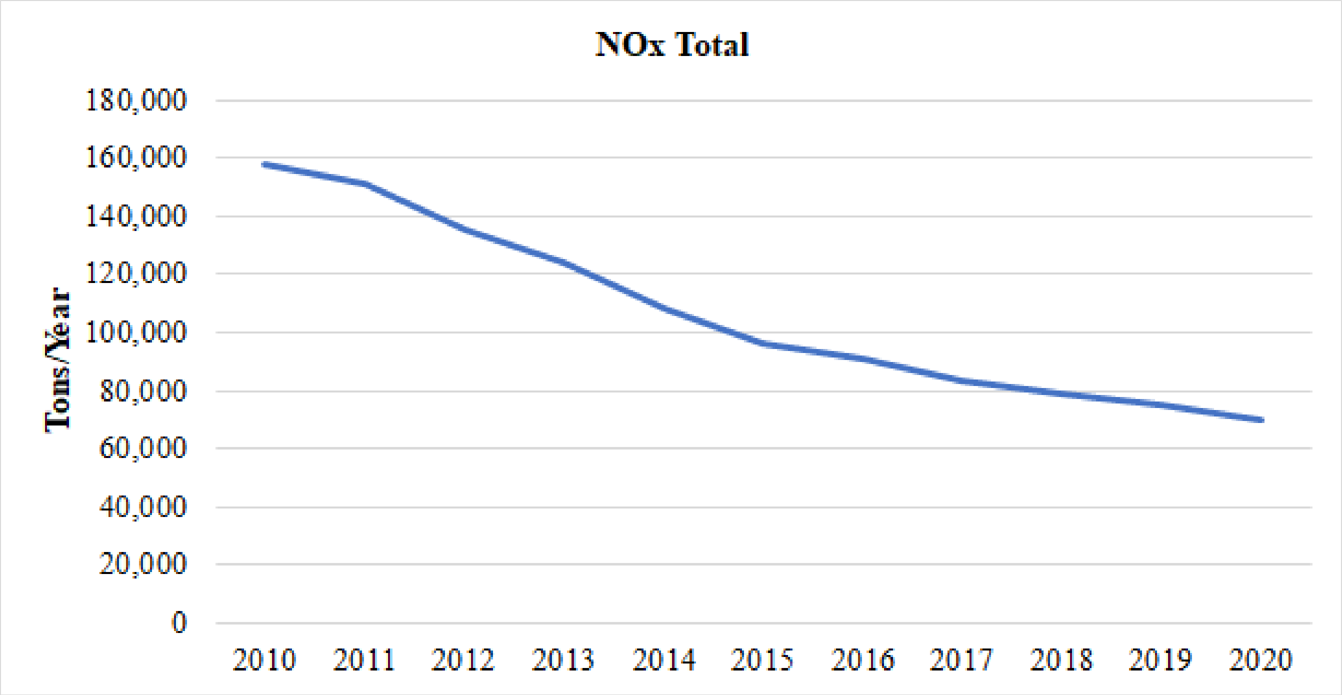


Figure 3.41. Evolution of total annual NOx emissions from transportation in California

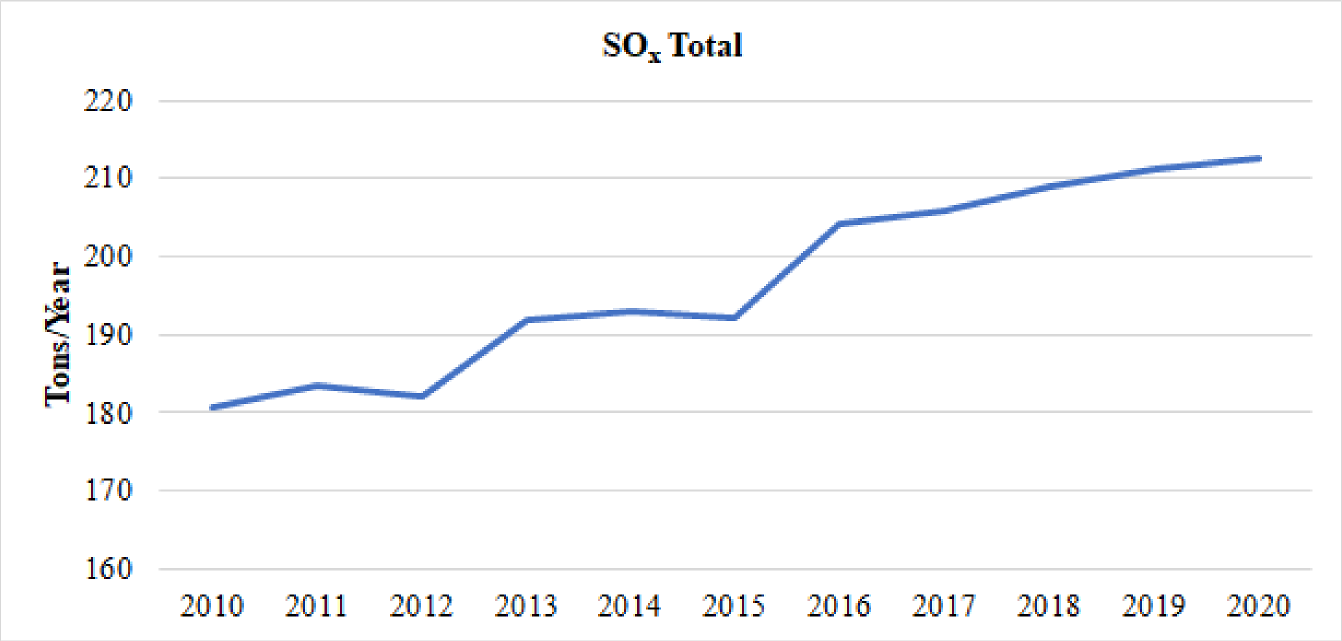


Figure 3.42. Evolution of total annual SOx emissions from transportation in California

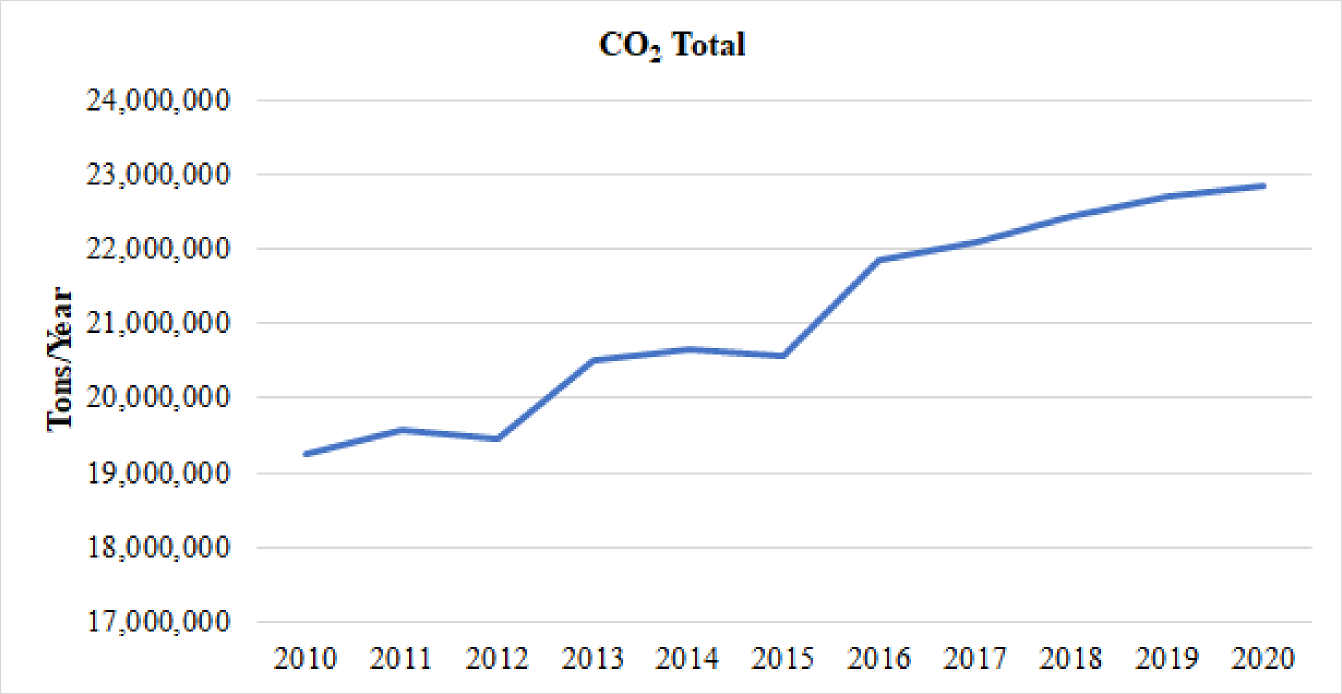


Figure 3.43. Evolution of total annual CO2 emissions from transportation in California

Finally, we note that the extraction, the processing, and the combustion of fossil fuels also generates greenhouse gases such as carbon dioxide (CO_2) or methane (CH_4), which contribute to global climate change, and the increase in frequency in many parts of the world of extreme events such as heat waves, floods, and tornados. As noted in Nissan and Conway (2018), mitigating climate change has many health co-benefits, including respiratory infections among children or ischaemic heart disease in adults

Overall, the last two decades have seen substantial declines in air pollution for most key pollutants generated by the transportation sector in California (with the exception of SO_x). As mentioned above, however, the health burden for PM, ozone, and NOx remains substantial and it still affects disproportionately children, the elderly, and racial minorities. It is also becoming urgent to tackle the increase of greenhouse gas emissions (see Figure 3.43) if California is to meet its climate objectives.

3.7.2 Active transportation

Increased automobile use not only increases emissions of GHGs and local air pollutants, but also increases the occurrence of physical crashes, injuries, and deaths. Increased reliance on automobiles also contributes to reduced rates of physical activity and increased rates of obesity. There are multiple ways of decreasing the external impacts of motor-vehicle use, including adding safety features (such as forward-collision warning, automatic emergency braking, blind spot detection, and pedestrian detection), switching transportation modes (i.e., taking transit instead of driving), increasing the cost of driving (i.e., by taxing fuel), or changing land use to decrease demand for driving.

One avenue that seems particularly promising is active mobility (e.g., walking and biking). Approximately half of the car trips in the United States are less than five miles, distances at which active mobility is feasible. Promoting active mobility could have a number of health benefits [189], [190], including a reduction in heart disease, stroke, diabetes, dementia, depression, and some cancers.

Based on experiences in Europe, Asia, and Australia, reducing car dependency in California will likely take a combination of “soft” and “hard” policies [191]. “Soft” policies include informational campaigns about the health benefits of active mobility and the adverse environmental impacts of driving, providing real-time information to support personal travel planning, convenient e-ticketing, and discounted or free public transportation passes. “Hard” policies include infrastructure changes, road and parking pricing, and higher vehicle taxation. In Denmark, for example, the registration tax for a new car varies between 85% and 105% of the car’s purchase price. The Danish government has also consistently invested in public transit and bicycling infrastructure, while implementing voluntary travel behavior change measures. As a result, approximately a third of Danes bike to work. The resulting health benefits of this high level of bicycling have been estimated to reduce annual sick days by 1.1 million in Copenhagen alone.

In terms of safety, annual fatalities for pedestrians ranged from 1.6–2.1 per 100,000 people between 2004 and 2014. For bicyclists, annual fatalities ranged from 0.3–0.4 per 100,000 people over the same period. These California values are notably higher than national averages.

3.8 Labor and employment

California’s transportation economy is a vast and complex system of diverse, interconnected industries. In order to examine the broader implications of the state’s transition to ZEVs for the transportation workforce, it is helpful to compartmentalize transportation-related industries into supply chains: sets of linked firms that each fulfill a distinct role with respect to a particular aspect of transportation, and which are interdependent upon each other. Three such supply chains are considered herein:

A. **Fuels**, the supply chain responsible for production, processing, and distribution of the energy sources Californians utilize to power transportation;
B. **Vehicles**, the supply chain that manufactures and distributes means of conveyance;
C. **Transportation services**, the supply chain that facilitates transport of passengers and goods.

Together, these three supply chains directly employed 850,529 workers across 71 distinct industries statewide in 2019 (see Figure 3.44). The majority of these are divided relatively equally among vehicles and transportation services, which employed 339,491 and 386,825 workers, respectively. Fuels, the smallest of the three chains in terms of workers, employed the remaining 124,213.

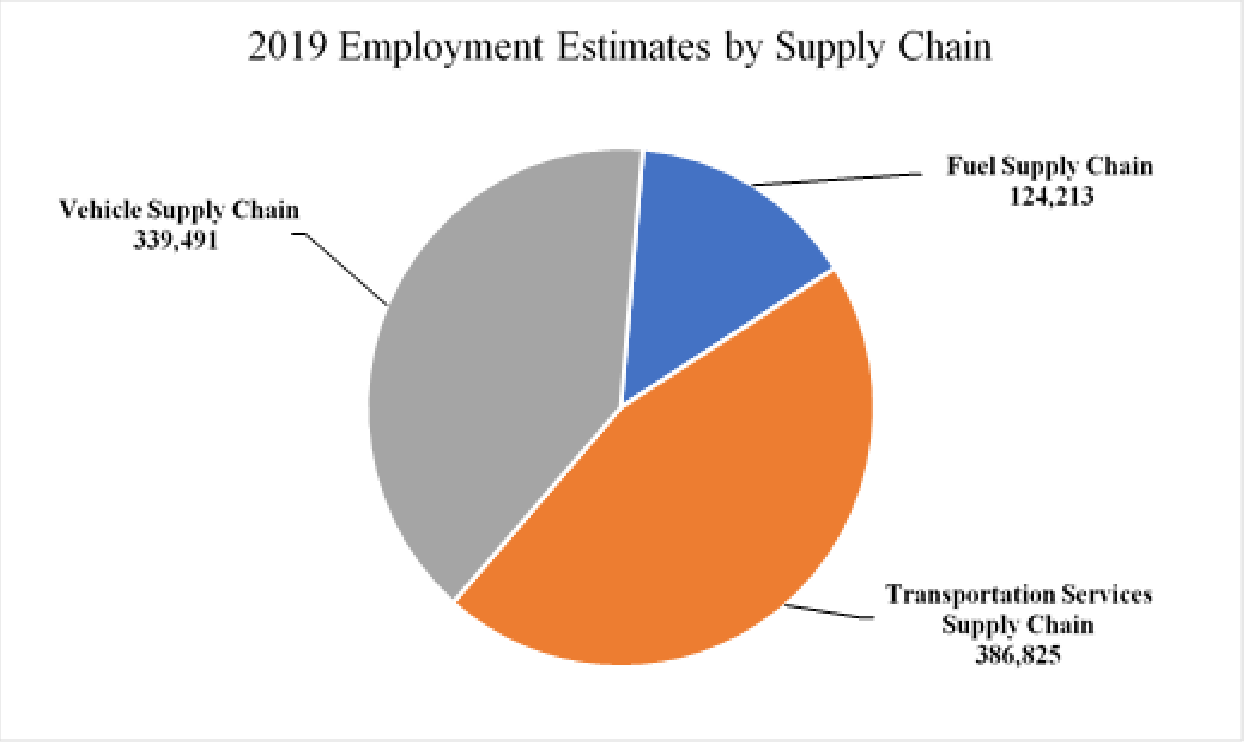


Figure 3.44. 2019 Employment Estimates by Supply Chain in California's Transportation Sector

3.8.1 Workforce Alignment of Industry Data between Studies 1 & 2

The selection of which industries to consider within Studies 1 and 2 is determined by the nature of the driving policy strategies upon which each study respectively focuses. Study 1 examines a variety of policies—including incentives focus upon vehicle purchase & leasing, fuels. refueling infrastructure, etc.—that shift consumer preferences and economic demand towards ZEVs. This shift will lead to ZEVs subsuming an increasing portion of the vehicles market currently dominated by ICEVs, a change that will lead to alternative fuels (predominantly electricity) displacing consumption of fossil fuels for transportation. This drop in demand for fossil fuels will ripple through the entire fossil fuel supply chain, causing a workforce contraction at the extraction, refining, and distribution stages. For this reason, Study 1 considers an expansive array of industries related to all parts of the fossil fuel supply chain.

In contrast, Study 2 constitutes an in-depth examination of policies aimed at reducing the production of transportation fossil fuel activity in California. These strategies include production quotas, well-head setbacks, restriction on new licenses, etc., and will likely lead to lower levels of extraction and refining in the state. Given this focus, Study 2 does not consider industries related to the distribution of fossil fuels to consumers, as distribution and consumption are likely to remain mostly unchanged as a result of Study 2's considered policies in isolation.

It is important to stress that, from the perspective of a typical consumer, implementation of these industry-side policies would simply produce an increase in gasoline and diesel prices. Short-term fuel demand tends to be relatively inelastic, and consumer response to these price changes is therefore unlikely to reduce transportation-related emissions in a sufficiently short time frame to meet the state's goals. However, increased fossil fuel prices lower the threshold for Study 1 policies to be effective. For instance, higher gasoline prices combined with incentive programs that reduce the barrier to ZEV adoption may make a given consumer transition much sooner than they would otherwise. The two sets of policies, while targeting distinct components of the transportation landscape, are thus complimentary.

Also important to note is that Study 2 has examined multi-year trends within the fossil fuel extraction and refining sectors, and uses averages from select years to provide baseline employment figures in these industries that are reflective of conditions in the longer term. Study 1's baseline figures are meant only to provide a point of reference for the discussion of employment shifts out to 2045. In the interest of having this reference reflect current conditions as closely as possible, only employment figures for 2019 are used.

Usage of data from past years in Study 2 also leads to inclusion of some industries that have since been reclassified, and therefore do not appear in Study 1's figures. However, the jobs represented by these defunct industry classifications are included under their more current NAICS codes.

Table 3.15. Consideration status and estimated employment for industries in California's fossil fuel supply chain across Carbon Neutrality Studies 1 & 2.

NAICS Code	Industry	Considered in:		Study 1 Estimate (2019)	Study 2 Estimate (2016-18)
		Study 1	Study 2		
4471	Gasoline Stations (Public)	Yes	No	186	
4471	Gasoline Stations (Private)	Yes	No	63,573	
23829	Other Building Equipment Contractors	Yes	No	10,763	
211120	Crude Petroleum Extraction	Yes	Yes	3,135	3,517
211130	Natural Gas Extraction	Yes	No	1,294	
213111	Drilling Oil and Gas Wells	Yes	Yes	3,024	2,434
213112	Support Activities, Oil-Gas Operations	Yes	No	6,792	
237120	Oil and Gas Pipeline Construction	Yes	Yes	10,016	10,580
324110	Petroleum Refineries	Yes	Yes	10,839	10,692

NAICS Code	**Industry**	**Considered in:** **Study 1**	 **Study 2**	**Study 1 Estimate (2019)**	**Study 2 Estimate (2016-18)**
324191	Petroleum Lubricating Oil and Grease Manufacturing	Yes	No	727	
324199	All Other Petroleum and Coal Products Manufacturinga	Yes	No	95	
325193	Ethyl Alcohol Manufacturing	Yes	Yes	225	225
333132	Oil and Gas Field Machinery and Equipment Manufacturing	Yes	No	1,374	
333914	Measuring, Dispensing, and Other Pumping Equipment Manufacturing	Yes	No	1,838	
424710	Petroleum Bulk Stations and Terminals	Yes	Yes	2,951	2,978
424720	Petroleum and Petroleum Products Merchant Wholesalers	Yes	Yes	5,139	4,678
454310	Fuel Dealers	Yes	No	2,654	
486110	Pipeline Transportation of Crude Oil	Yes	Yes	508	617
486210	Pipeline Transportation of Natural Gas	Yes	No	390	
486910	Pipeline Transportation of Refined Petroleum Products	Yes	Yes	775	634

The goal of this chapter is to broadly describe the present-day state of these supply chains as it relates to labor and employment in California. We explore how each chain is likely to be impacted by the transition to ZEVs, the magnitude of these supply chains and their component industries in terms of the number of jobs they provide, and the quality of jobs as measured by wages and benefits. Wage figures presented herein incorporate both salary and several types of benefits. However, unionization rates—a key measure of job quality, and one correlated with higher wages—have thus far been difficult to identify for specific California industries. On a nation-wide basis, workers in industries related to transportation supply chains (e.g., construction, extraction, production, and transport) had higher unionization rates in 2019 (between 12.8% and 18.5%) than the national average (10.5%), and California's overall unionization rate (16.5%) also exceeded the national average [192]. One could make reasonable assumptions regarding unionization in California's transportation-related industries based on these trends, but more refined data collection is needed.

We also highlight notable geographic areas in which certain industries are concentrated, and wherever possible, characterize the demographics of certain industries under scrutiny. However, at this point in time, information detailing the racial, ethnic, gender, and age characteristics of the state's transportation workforce in a systemic fashion has not been found.

The information that follows will thus serve as a baseline for future policy analysis. In this future analysis we will model a middle-of-the-road workforce scenario for the three transportation supply chains and assess how various policy options may assist California policy makers in navigating the transition to ZEVs. Apart from this work, the state may wish to consider options for addressing the aforementioned lack of workforce unionization and demographic data through a large-scale survey, analysis of census data, or similar efforts.

3.8.2 Employment in the fuels supply chain

California's fuels supply chain is predominantly composed of two fairly distinct sets of industries: those related to the production of fossil fuels, and those that produce electricity. Workers in the fossil fuel supply chain extract and convert feedstock (e.g., crude oil) into transportation fuels (e.g., gasoline), distribute those transportation fuels to refueling stations, and operate said stations for wholesale and retail use by drivers or fleet operators. Workers in the electricity supply chain perform similar tasks, but more skewed towards constructing and operating generation and distribution infrastructure.

An important note: wage figures discussed for workers by industry below incorporate several non-income elements related to job quality, including stock options, benefits, and employee contributions to retirement. Except where noted, these data are derived from the Quarterly Census of Employment and Wages (QCEW) data from the U.S. Bureau of Labor Statistics (BLS).

3.8.2.1 Transition Impacts

Of the three transportation supply chains, the transition to ZEVs will have the greatest impact on workers within the fuels supply chain. A shift towards electricity and hydrogen in place of combusting fossil fuels for transportation will reduce demand for petroleum products. Consequently, employment in oil and gas extraction, fossil-fuel refining, and fossil-fuel distribution industries will drop. The degree to which this occurs in the upstream and midstream portions of the fossil fuel supply chain will depend on the availability and magnitude markets for petroleum products outside California. Additionally, because the oil- and gas-extraction industries and in-state refineries will continue to produce fuel for aviation, maritime, and out-of-state consumers for the time being, it is unlikely that employment in these industries will be completely eliminated as a result of California's transition to ZEVs. However, such a transition may eventually eliminate employment associated with the distribution of fossil fuels for transportation (i.e., the delivery and sale of gasoline and diesel).

However, the ZEV transition will create new supply chains to provide alternative energy for transportation. Electricity will likely be the dominant player in this space, but industries offering other fuels like hydrogen will also expand. Employment in clean electricity generation and carbon-neutral fuel production and electricity transmission and distribution will increase. New charging station and refueling infrastructure will create new jobs for the construction, operation, and maintenance for these facilities and the manufacturing of necessary components and equipment. In the long-term, California's renewable energy industries will also expand to meet increased demand, as will electricity providers like utilities and CCAs as they increase their delivery of electricity as a transportation fuel.

3.8.2.2 Magnitude

In 2019, California's fuels supply chain had approximately 124,213 workers across 9,655 establishments (Table 3.16 and Table 3.17). Gasoline stations dominate these figures, comprising a significant majority of establishments (7,064) and a slim majority of workers (63,573). Oil and gas pipeline construction, other building equipment contractors, and petroleum refineries are in a virtual three-way tie for second place, each with between 10,000 and 11,000 workers. Employment figures for the electricity supply chain are quite low (1,091), as they are scaled to the (very low) proportion of electricity that is currently used for transportation.

3.8.2.3 Quality and Qualifications

Earnings within the fossil fuel supply chain have a wide range, with gasoline station operators earning $28,296 annually while workers classified under the Crude Petroleum Extraction NAICS code earn an estimated $285,697 annually, on average. The electricity sector's earnings range is narrower by comparison, with the lowest earners being electrical contractors ($78,506 annually) and the highest earners being workers within electric power generation industries ($156,563 annually), as classified by NAICS code.

Skills and educational requirements for employment exhibit similar variation, ranging from minimal (i.e., high school diploma) to a four-year degree or highly technical training. A small portion (11%) of California's oil and gas industry employees had less than a high school education in 2017 [193].

3.8.2.4 Geographic Distribution

Some fuel supply chain industries are fairly homogeneous in their distribution throughout the state. The quintessential example is gasoline stations, and fossil fuel pipelines crisscross the state south of Sacramento. On the electricity-generating side, jobs related to power generation and distribution are similarly dispersed, as power plants and substations are found throughout California.

However, other parts of the fuel supply chain are limited to particular geographic areas. Petroleum refineries are concentrated in the Los Angeles, Bakersfield, and San Francisco Bay Areas [194]. Most oil extraction sites are located in Southern California proximate to refining facilities, with the vast majority of active wells being located in the San Joaquin Valley sub-region (LAEDC 2019) [193]. The San Joaquin Valley is heavily represented in several other measures of industry activity as well. NG extraction sites are mostly contained in the Sacramento Valley area in Northern California [194].

As a caveat, while the location of particular infrastructure certainly correlates with related employment, more research is called for to assess the strength of this link.

3.8.2.5 Demographics

Current demographic data for the fuel supply chain comes from the U.S. Census Bureau's Quarterly Workforce Indicators (QWI) dataset. In 2019, the industries in California's fuel supply chain were predominantly White (between 67.15% and 86.71% of industry workers), with the next highest racial group being Asian (between 3.59% and 22.98%). No other racial group in this supply chain attained double digit percentages in 2019. Worker sex were similarly stratified in 2019, with men making up a vast majority of workers in the fuel supply chain (from 56.58% to 87.85%). Regarding ethnicity, most workers were Hispanic or Latino (from 54% to 78.64% of industry workers).

Table 3.16. 2019 Employment Estimates for California's Fossil Fuel Supply Chain

Industries	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Crude Petroleum Extraction	211120	86	3,135	$285,697
Natural Gas Extraction	211130	38	1,294	$132,088
Drilling Oil and Gas Wells	213111	123	3,024	$144,655
Support Activities, Oil-Gas Operations	213112	258	6,792	$84,284
Oil and Gas Pipeline Construction	237120	176	10,016	$88,333
Other Building Equipment Contractors	23829	815	10,763	$94,870
Petroleum Refineries	324110	106	10,839	$174,905
Petroleum Lubricating Oil and Grease Manufacturing	324191	32	727	$81,919
All Other Petroleum and Coal Products Manufacturing[a]	324199	4	95	$93,366
Oil and Gas Field Machinery and Equipment Manufacturing	333132	36	1,374	$74,397
Measuring, Dispensing, and Other Pumping Equipment Manufacturing	333914	78	1,838	$82,690
Petroleum and Petroleum Products Merchant Wholesalers	424720	372	5,139	$90,171
Gasoline Stations (Public)	4471	8	186	$28,918
Gasoline Stations (Private)	4471	7,064	63,573	$28,296
Fuel Dealers	454310	273	2,654	$62,253

Industries	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Pipeline Transportation of Crude Oil	486110	29	508	$108,244
Pipeline Transportation of Natural Gas	486210	25	390	$143,470
Pipeline Transportation of Refined Petroleum Products	486910	64	775	$120,545
Employment Totals		9,587	123,122	

Note. Estimated employment based on existing employment multiplied by the percentage of EV electricity consumption in comparison to total electricity consumption in California, roughly 0.68%.

Table 3.17. 2019 Employment Estimates for California's Electricity Supply Chain

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Electric Power Generation	22111	2	92	$156,563
Electric Power Transmission and Distribution	22112	1	31	$138,832
Power and Communication Line and Related Structures Construction	237130	3	121	$120,993
Electrical and Wiring Contractors	23821	65	761	$78,506
Turbine and Turbine Generator Set Units Manufacturing	333611	1	31	$130,256
Electrical Equipment Manufacturing	33531	2	55	$83,170
Employment Totals		74	1,091	

3.8.3 Employment in the Vehicle Supply Chain

Workers in California's vehicle supply chain manufacture LDVs, MDVs, and HDVs, and the replacement parts necessary to maintain these vehicles. They also perform required maintenance and repairs for vehicles.

3.8.3.1 Transition Impacts

Unlike the fuels supply chain, the vehicle supply chain is unlikely to undergo a dramatic transformation in response to the state's transition to ZEVs. However, there will be notable changes to the products being produced and the technology those products utilize within the vehicle manufacturing sector as ICEVs are phased out in favor of BEVs, PHEVs, and FCVs. No vehicle manufacturer currently produces and assembles all components in-house, however, muting the impact of the transition on vehicle producers themselves. Instead, vehicle manufacturers purchase components from third parties and assemble these components at a vehicle manufacturing plant. The decentralized nature of this supply chain means that many of the negative impacts of the transition on traditional component manufacturing will occur outside the state. However, there will likely be some disruption to manufacturers as they retrain and shift their workforce to focus on ZEVs.

This will likely be accompanied by an expansion of the upstream industries supplying vehicle manufacturers with battery components and the industries producing the raw inputs for battery manufacturing. Similar, though likely smaller, increases will occur for fuel cell manufacturing.

In the downstream portion of the supply chain, employment for combustion-engine and power-train maintenance and repair will decline. Because all-electric vehicles require less maintenance than do fossil-fuel vehicles, we may see reductions in automotive repair shops, although employment in body shops needed to repair damage from vehicle collisions will not be impacted. Nascent trends are emerging wherein EV manufacturers (namely Tesla) are adopting a proprietary maintenance and repair model with branded repair shops, backed up by threats of litigation. Should this practice become more common, it would threaten small and independently owned automotive repair businesses. In contrast, the fundamental business model of vehicle dealerships should not be substantially altered by the ZEV transition, independent of other trends that may affect overall demand for personal vehicles.

Should all-electric micromobility vehicles such as scooters, bicycles, and neighborhood electric vehicles continue to become more common, employment will increase with the expansion of these industries. However, demonstrated volatility and worrisome fiscal situations for companies operating in this space make such expansion uncertain, and other factors discussed in Section 1.7.3 below call into question how attractive the micromobility industry is as a source of employment. The potential for this industry to create jobs also depends on whether required parts are manufactured and assembled within California or out of state. Potential does exist for the development of micromobility manufacturing capacity in the state, but whether it will emerge is purely speculation at this point.

3.8.3.2 Magnitude

In 2019, California's vehicle supply chain had approximately 346,398 workers across 26,643 establishments (Table 3.18, 19, & 20). A sizeable portion of these workers (118,818) are employed by new car dealers. Other major industries include general automotive repair (39,859) and private automotive parts and accessories stores (34,950). The current employment totals for industries specific to California's EV supply chain are fairly small (7,816).

3.8.3.3 Quality and Qualifications

The earnings among vehicle supply chain workers tend to be lower, on average, than the fuels sector, with most vehicle supply chain industries having an average annual income between $30,000 and $60,000. In only one industry, miscellaneous electrical equipment manufacturing, do average annual wages exceed $100,000. The largest industry by employment, new car dealers, slightly exceeds the typical range with average annual wages of $68,473. As in the discussion of the fuels supply chain, these figures include several types of non-wage benefits.

Educational and skill barriers to entry for workers in the vehicle supply chain cover a wide range. At one end, entry-level positions in small-scale assembly facilities and automotive repair may require a high school diploma or less. Jobs closer to the industry median commonly require vocational training or certifications beyond the high school level, while the highest echelons of engineers and other professionals will typically have a four-year degree or graduate-level education.

3.8.3.4 Geographic Distribution

Economic cluster analysis indicates that regional specialization in automotive manufacturing is low in California, with only the Los Angeles metropolitan area having a notable location quotient—a measure of the degree to which a region is aligned towards a particular industry compared to the nation as a whole—of 0.32 [195]. For comparison, the Detroit, MI metropolitan area has an automotive specialization of 6.74. Jobs related to automotive manufacturing are also concentrated in Los Angeles and the adjoining Riverside area. Ongoing trends and current wage figures indicate that the San Jose area may be a budding center for manufacturing of automotive technology and components.

With respect to downstream sales and maintenance businesses, no data on general geographic trends in vehicle distribution (i.e., dealerships) has yet been identified, though industry groups like the California New Car Dealers Association may be able to provide some insights in this area. Intuitively, dealerships and the large number of jobs they provide are likely to be clustered in high-population urban areas, given the minimum demand requirements necessary for such businesses to remain solvent.

3.8.3.5 Demographics

California’s vehicle supply chain is highly diverse and highly fragmented. As such, no source of industry-wide demographic information has been identified at this time.

Table 3.18. 2019 Employment Estimates for California's General Vehicle Supply Chain

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Industrial Truck, Trailer, and Stacker Manufacturing	333924	36	440	$52,610
Motor Vehicle Manufacturing	3361	81	17,870	$94,361
Motor Vehicle Body Manufacturing	336211	89	3,412	$57,554
Motor Vehicle Steering and Suspension Components (except Spring) Manufacturing	336330	44	608	$46,417
Motor Vehicle Brake System Manufacturing	336340	16	588	$54,758
Motor Vehicle Seating and Interior Trim Manufacturing	336360	51	903	$52,181
Motor Vehicle Metal Stamping	336370	15	387	$50,702
New Car Dealers	441110	1,998	118,818	$68,473
Used Car Dealers	441120	1,398	12,825	$51,511
Automotive Parts and Accessories Stores (Public)	441310	3	14	$27,774
Automotive Parts and Accessories Stores (Private)	441310	3,544	34,950	$35,814
Passenger Car Rental	532111	1,403	17,788	$49,684
Passenger Car Leasing	532112	48	204	$87,289
Truck, Trailer, and RV Rental and Leasing	532120	604	7,619	$57,618
Other Commercial and Industrial Machinery Equipment Rental and Leasing	532490	1,238	12,016	$67,498
Other Automotive Mechanical and Electrical Repair and Maintenance	811118	542	2,837	$46,546
All Other Automotive Repair and Maintenance	811198	1,236	4,869	$47,227
Employment Totals		12,346	243,055	

Table 3.19. 2019 Employment Estimates for California's Motor Vehicle Supply Chain

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Other Engine Equipment Manufacturing	333618	28	415	$91,699
Motor Vehicle Gasoline Engine and Engine Parts Manufacturing	336310	117	2,297	$66,355
Motor Vehicle Transmission and Power Train Parts Manufacturing	336350	57	955	$68,331
Other Motor Vehicle Parts Manufacturing	336390	174	4,614	$52,345
Motorcycle, Bicycle, and Parts Manufacturing	336991	123	1,899	$51,769
Automobile and Other Motor Vehicle Merchant Wholesalers	423110	600	11,975	$85,843
Motor Vehicle Supplies and New Parts Merchant Wholesalers	423120	2,006	23,162	$59,619
Motor Vehicle Parts (Used) Merchant Wholesalers	423140	217	2,293	$58,273
General Automotive Repair	811111	9,681	39,859	$46,156
Automotive Exhaust System Repair	811112	222	651	$38,149
Automotive Transmission Repair	811113	457	1,578	$42,596
Automotive Oil Change and Lubrication Shops	811191	669	5,829	$31,614
Employment Totals		14,351	95,527	

Table 3.20. 2019 Employment Estimates for California's Electric Vehicle Supply Chain

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Storage Battery Manufacturing	335911	45	1,686	$72,446
Miscellaneous Electrical Equipment Manufacturing	335999	201	6,130	$106,820
Employment Totals		246	7,816	

3.8.4 Employment in the Transportation Services Supply Chain

Workers in the transportation services supply chain drive a variety of vehicles to transport passengers and goods, manage and maintain both public and private vehicle fleets, and provide a range of public transit services.

3.8.4.1 Transition Impacts

The transition to ZEVs is unlikely to significantly impact employment within the transportation services supply chain. The fundamental operating model of transportation services firms and agencies will not be altered by changes to the types of vehicles they use to provide their services, though requirements for maintenance personnel may drop as higher-longevity EVs are adopted. Demand for professional drivers and the type and size of fleets maintained should not be affected by the transition itself, assuming affected entities have the capital to replace their fleet entirely. Here, we treat the impacts of this transition as distinct from the transition towards autonomous and connected vehicles and from land use or transportation policies which may affect overall demand for transportation. These impacts will be felt regardless of whether Californians' are utilizing ZEVs or fossil fuel-burning vehicles, and will depend on the trajectory of a separate set of vehicle technologies and public policies.

One potential exception to this low-impact characterization is the taxi industry, which has continued to operate a large number of "legacy" ICEVs. The costs of phasing out these vehicles in favor of ZEVs *en masse* over a relatively short time period could be a major hurdle for taxi firms.

Workers within related industries are employed by rental car companies, car sharing companies, public transit agencies, municipal or corporate fleet managers, delivery companies (e.g., FedEx, UPS, Amazon, etc.), long-haul freight companies, and TNCs. As aforementioned, TNC drivers have often been employed as independent contractors, as have taxi drivers, food and package delivery persons, and workers driving drayage trucks and long-haul tractor trailers.

3.8.4.2 Magnitude

In 2019, California's transportation services supply chain had approximately 386,825 workers across 22,564 establishments (Table 3.21). The vast majority of these (305,227) work in industries related to goods transportation (Figure 3.45). The three largest industries by employee count—General Freight Trucking (93,912), Couriers and Express Delivery Services (85,029), and Specialized Freight Trucking (40,716)—together compose a majority of employment in this supply chain.

As noted previously, these figures do not include independent contractors. This creates particularly notable challenges for estimating transportation services employment, as major TNCs like Uber and Lyft have historically classified their drivers as independent contractors.

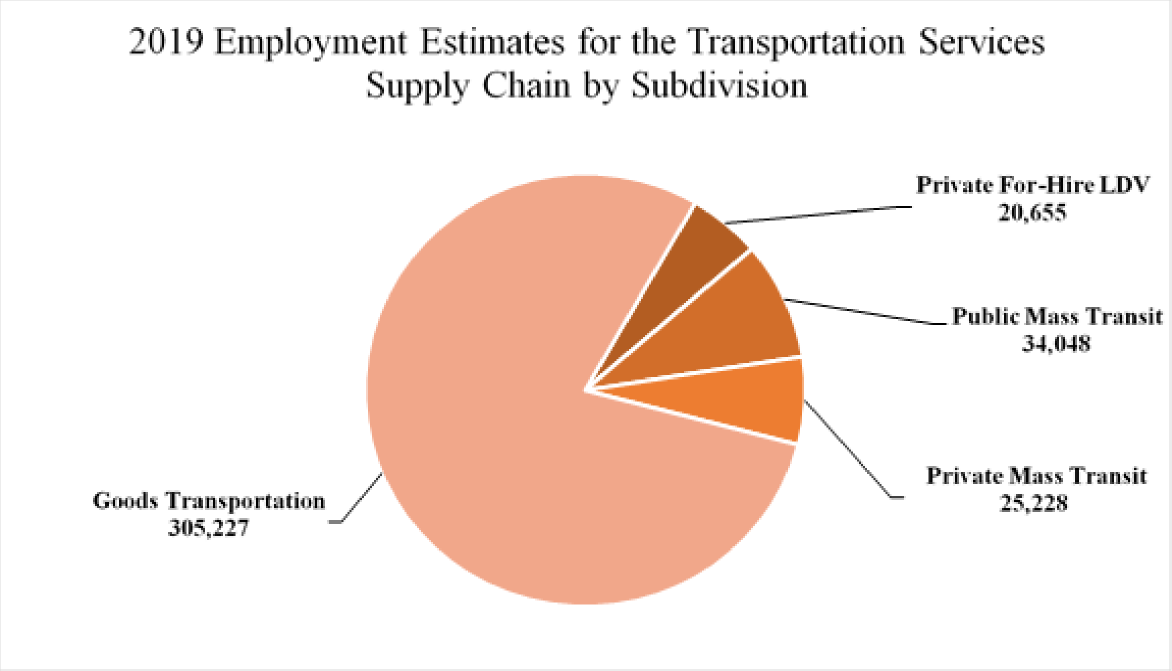


Figure 3.45. 2019 Employment Estimates for the Transportation Services Supply Chain by Subdivision

3.8.4.3 Quality and Qualifications

Similar to the vehicle supply chain, earnings among transportation services employees tend to fall within the $30,000 and $60,000 annual wage range. Interestingly, public employees consistently out-earn their private counterparts across multiple industries. This trend is likely due, in part, to the action of public sector unions.

The aforementioned three largest industries in the supply chain all fall into this $30,000 to $60,000 range, with trucking industries falling towards the higher end. In only two industries does BLS' QCEW data report average annual wages exceeding $100,000: public support activities for road transportation and taxi service. The latter of these reports an outlandishly high figure ($432,072), which may be the result of excluding rank-and-file drivers from the NAICS code classification. A more representative figure for the typical taxi employee is $36,920 average annual wages, derived from BLS' Occupational Employment Statistics (OES). This figure includes passenger vehicle drivers within the industry, though it may not be completely representative as it also includes employees in limousine services and some TNC contractors.

Access issues for workers in these spaces skew more towards monetary barriers than educational or skill barriers, as drivers may need to obtain particular licenses or pay for trainings. These barriers are especially high for TNC drivers, as since their inception these companies have sought to offload the most burdensome capital costs—most obviously, the vehicles themselves—onto their workers.

3.8.4.4 Geographic Distribution

Generally, transportation services employment is distributed loosely around particular epicenters related to the goods and freight being transported (e.g., ports) and the populations being served, whether passengers or consumers (i.e., high-population urban areas). This trend tends to extend to both rank-and-file workers and contractors and higher-level white-collar jobs within companies, which tend to locate corporate offices in large cities.

3.8.4.5 Demographics

As with the vehicles supply chain, California's transportation services supply chain is made of a multitude of distinct and disparate companies and agencies, both public and private. As such, no source of demographic data on an industry- or supply chain-wide scale has been identified at this time.

3.8.4.5.1 Addressing Micromobility

While not a central focus of this report, the rise of micromobility services in recent years and their theoretical potential to help fill a niche in transportation services makes them worth addressing briefly. Unfortunately, the ability to discuss workforce baselines and trends in the micromobility industry is severely limited by opaque corporate policies and worker (mis)classification practices. Companies operating in this space have proved reluctant to share employment or operations data and some emulate TNCs by classifying workers as independent contractors, hindering accurate assessment of their workforce profile.

These workers' positions are stereotypically low quality, with low wages and poor job security. The precarity of this work is compounded by the high volatility the industry has exhibited thus far, even more so as the COVID-19 pandemic has created a precipitous drop in demand and companies have laid off large parts of their workforce. Combined with the fact that micromobility options—the quintessential example being e-scooters—have questionable environmental benefits at best, there is scant evidence that the industry should be prioritized as an avenue to reducing emissions while creating high-quality jobs.

Table 3.21. 2019 Employment Estimates for California's Transportation Services Supply Chain

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
General Freight Trucking	4841	9,811	93,912	$53,764
Specialized Freight Trucking	4842	3,724	40,716	$55,536
Bus and Other Motor Vehicle Transit Systems (Public)	485113	61	16,049	$75,179
Bus and Other Motor Vehicle Transit Systems (Private)	485113	76	4,163	$45,493
Interurban and Rural Bus Transportation (Public)	485210	8	1,045	$58,927
Interurban and Rural Bus Transportation (Private)	485210	28	1,069	$42,167

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Taxi Service	485310	160	10,527	$432,072***
Limousine Service*	485320	642	5,400	$40,774
School and Employee Bus Transportation (Public)	485410	106	5,488	$47,629
School and Employee Bus Transportation (Private)	485410	188	11,380	$39,991
Charter Bus Industry	485510	175	3,188	$45,645
Special Needs Transportation	485991	443	10,485	$37,184
All Other Transit and Ground Passenger Transportation*	485999	307	4,728	$51,678
Scenic and Sightseeing Transportation, Land (Public)	487110	3	492	$39,867
Scenic and Sightseeing Transportation, Land (Private)	487110	144	2,140	$51,995
Motor Vehicle Towing	488410	1,279	12,075	$43,190
Other Support Activities for Road Transportation (Public)	488490	5	489	$104,012
Other Support Activities for Road Transportation (Private)	488490	390	3,288	$43,939
Postal Service (Public)**	491110	1,402	33,234	$66,089
Postal Service (Private)	491110	105	742	$36,008
Couriers and Express Delivery Services	492110	976	85,029	$46,290
Local Messenger and Local Delivery	492210	1,088	16,717	$48,419
Solid Waste Collection (Public)	562111	1	7	$43,200

Industry Title	NAICS Code	Establishments	Estimated Annual Employment	Estimated Annual Wages
Solid Waste Collection (Private)	562111	858	17,462	$67,224
Hazardous Waste Collection	562112	130	4,192	$70,715
Other Waste Collection	562119	154	1,141	$52,312
Automobile Driving Schools	611692	300	1,667	$29,096
Employment Totals		22,564	386,825	

*TNCs Lyft and Uber fall under different NAICS codes, 485320 (Limousine Services) and 485999 (All Other Transit and Ground Passenger Transportation) respectively. However, this data is from before the enactment of California's AB5, so drivers are not counted among these estimates.

**USPS carrier employment estimate based on BLS percent of industry employment, 53.78%.

***This high number has two plausible explanations: the wage estimate omits driver expenses (leasing costs for vehicles and the cost of insurance), or, since these data only capture employees (and may therefore exclude taxi drivers themselves), the revenue generated by taxi companies is distributed across a small number of people. See above for discussion.

4 Scenarios

This section explores a principal low-carbon scenario and several "side case" scenarios to consider pathways to reach the carbon neutrality target in 2045. These are compared to the "business-as-usual" (BAU) scenario, in terms of changes needed in vehicles, fuels, travel, and related factors to achieve the target, as well as some of the direct costs of doing so.

4.1 Business-as-Usual Scenario

4.1.1 Concept

This study builds low-carbon projections off of a "business-as-usual" (BAU) projection. The BAU projection reflects past trends and how those trends may continue (or change) into the future in the absence of new policies. This projection also considers how existing policies may "bend the curve" of CO_2 and other key metrics of interest. We describe the status of the BAU projection and the underlying assumptions below.

The BAU projection (and other projections) are summarized using the UC Davis' Transportation Transitions Model (TTM). This model was used in an "80-in-50" study [196], which assessed a reduction of 80% of CO_2 emissions from road vehicles in California by 2050. That study also developed a BAU projection for California that helps form the basis of the BAU for this report. The BAU here has been further calibrated to the California Air Resources Board's (CARB's) EMFAC (EMission FACtor) data and modeling efforts, and specific policies and their potential impacts have been taken into account.

Life cycle greenhouse gas (GHG) emissions from transportation fuels in the BAU scenario decline from 208 million tonnes CO_2e in 2017 to 121 in 2045, a reduction of 42%. Absent monumental advances in fuel economy and ethanol carbon intensity coupled with massive investments in net-negative carbon capture and sequestration (CCS) projects, such as direct-air capture to CCS or bioenergy to CCS, the BAU scenario comes nowhere close to achieving the SB 32 target, the 2045 carbon neutrality goal, or California's international commitments to decarbonization.

4.1.2 Tools

The TTM is a transparent spreadsheet model that projects California road transportation from 2000 to 2050 in terms of vehicle sales and stocks, vehicle travel, energy use, and CO_2 emissions. The TTM is calibrated to CARB Vision/EMFAC but also takes into account other historical data and estimates that in some cases deviate from this source. The TTM includes a wide range of technology and cost data and projections, as well as cost factors for vehicles and fuels that allow estimation of the magnitudes of the investments and subsidies required to achieve a transition to low and zero emission transportation.

Based on the Argonne VISION model modified by CARB [197], the TTM includes relevant economic costs associated with zero-emission vehicles based on a detailed component-level analysis for key technologies, such as fuel storage, batteries, fuel cells, and electric drivetrains. As in the rest of this analysis, the TTM is disaggregated into different categories. Disaggregation makes it possible to determine which vehicle and fuel technologies may be appropriate for specific vehicle types (e.g., battery electric vehicles [BEVs] are currently unsuitable for long-haul trucks but possible for short-haul trucks).

The TTM comprises a vehicle module and a fuel module, as shown in Figure 4.1. The vehicle module covers vehicle sales, stocks, travel, efficiency, energy use, and CO_2 emissions for California road vehicles, broken into two light-duty vehicle (LDV) classes, two bus types, three medium-duty truck types, and three heavy-duty truck types.

The fuel module calculates fuel costs and carbon intensities. This fuel module represents economic costs and includes a detailed representation of fuel infrastructure deployment and scale required to adequately assess the full impacts of shifting to low-carbon fuels and vehicles. The fuel module provides a representation of all the necessary resource, production, transport, and refueling station elements in the TTM. The fuel module includes four primary elements of a generic fuel pathway:

- **Resource supplies.** Energy resources used in the production of the alternative fuel, plus the prices and quantities of these resources, are modeled.
- **Production/conversion facilities.** Production facilities are modeled with information about resource inputs, conversion efficiency, and facility costs.
- **Fuel transport.** Finished transportation fuels must be transported to the refueling stations. This process is modeled from a cost and energy input perspective.
- **Refueling stations.** The cost and energy inputs of building refueling infrastructure is modeled.

The fuel module receives information about fuel demand and number of vehicles from the vehicle module and outputs fuel costs and fuel carbon intensities.

The model also can be interacted with a separate “truck choice” model to help estimate future vehicle sales shares by technology type for different truck classes. In this project, the truck technology analysis will be handled separately by the freight task group.

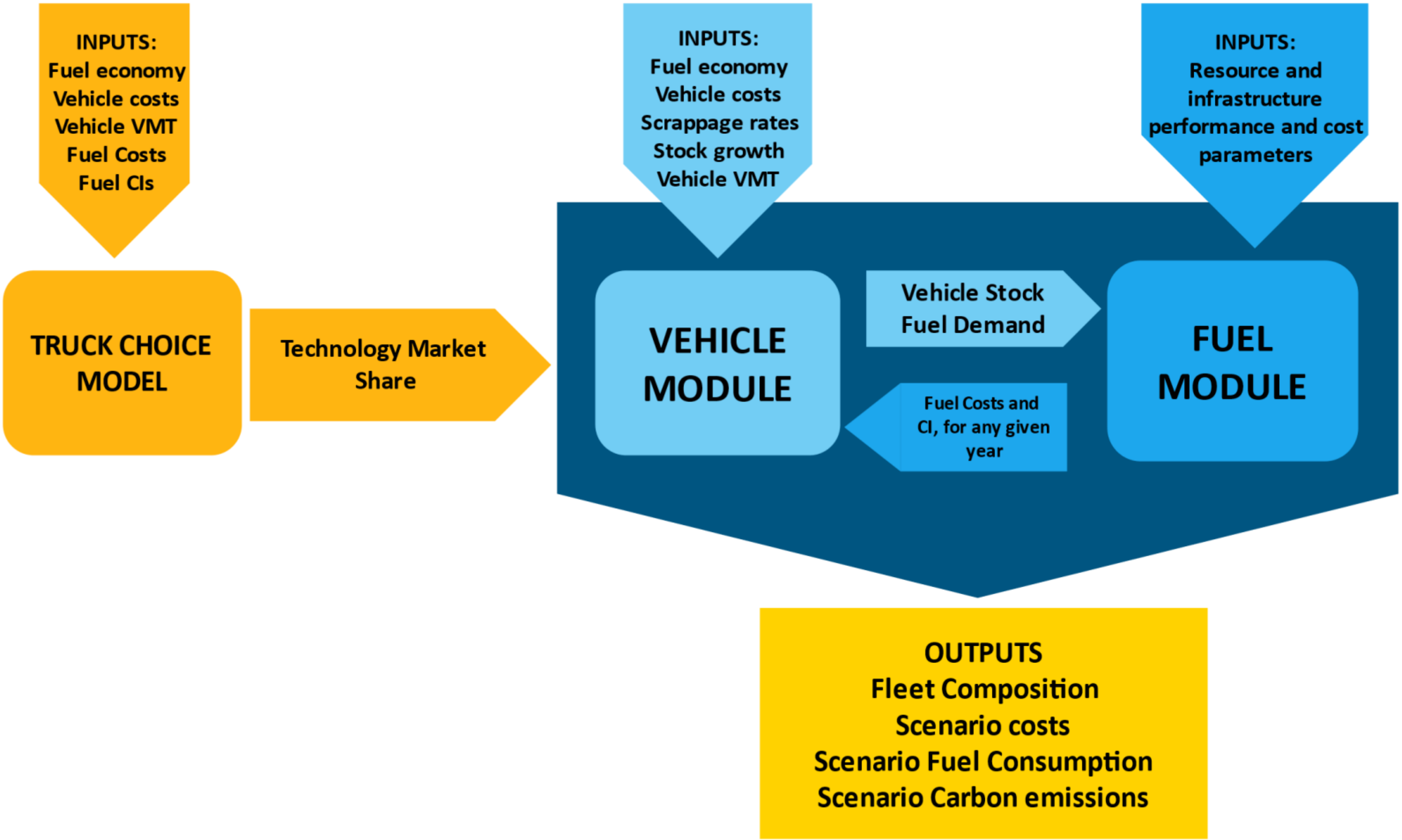


Figure 4.1. Basic modeling flow in the Transportation Transitions Model (TTM). (VMT, vehicle miles traveled; CI, carbon intensity.)

4.1.3 Policy approach

The BAU scenario reflects existing trends and considers how these trends will be affected by a number of existing California transportation and CO_2 related policies. Table 4.1 summarizes these and indicates how the treatment of these policies here is similar to or different than CARB's treatment in their current scoping plan development.

Table 4.1. Existing Policies to target reduction of GHG emissions in the transportation sector

Policy	General impact	Proposed treatment
Low-carbon fuel standard (LCFS)	20% reduction in average transportation fuel carbon intensity (CI) by 2030 vs 2010	We assume this occurs and further assume that the LCFS target maintains a 1.25% per year reduction in CI after 2030.
LDV ZEV sales requirements in 2025	1.5 million target based on credit system.	We assume this is achieved and that ZEV stocks reach about 3.3 million by 2030 and rise slowly thereafter (sales level off at around 450k per year).
LDV ZEV cumulative sales by 2030	5 million Governor's target	We do not assume this is met due to a lack of existing supporting policies.
Municipal transit buses sales share by 2030	100% ZEV sales share by 2030	We assume this is achieved and then stays constant. We assume a high share of these are BEVs, with some FCEVs.
MDV/HDV ZEV 2030 Advanced Clean Truck (ACT) rule	Not included in BAU; was passed during 2020 and we set policies for BAU based on the early 2020 situation.	This policy will, if fully implemented and achieved, result in up to 60% ZEV sales shares for various truck types by 2035. Since not to be considered in the BAU, this is factored into the low-carbon scenarios. Instead, for the BAU scenario, we have assumed electrification of some delivery (class 3-7) trucks related to the last mile delivery regulation. ZEVs constitute 2.5% of sales in 2021, increasing to 10% percent in 2025. The overall average for all trucks is about 2% ZEV sales by 2025.
VMT	SB-375 target - 10% reduction by 2020	California did not achieve VMT reductions by 2020. The VMT task team is looking at other dynamics, but for the BAU scenario, VMT per capita is not expected to deviate much from a constant trend.

LCFS, Low Carbon Fuel Standard; CI, carbon intensity; ZEV, zero emission vehicle; LDV, light-duty vehicle; BEV, battery electric vehicle; PHEV, plug-in hybrid electric vehicle; FCEV, fuel cell electric vehicle; MDV, medium-duty vehicle; HDV, heavy-duty vehicle; VMT, vehicle miles traveled

4.1.4 Results

The resulting BAU scenario includes a range of projections described above, such as growth in travel that is consistent with population growth. There is also a proportional growth in sales and stocks of vehicles to support this travel. This leads to a BAU assumption of significant growth in both LDV travel (60% growth, 2010–2045) and truck travel (70% growth; Figure 4.2).

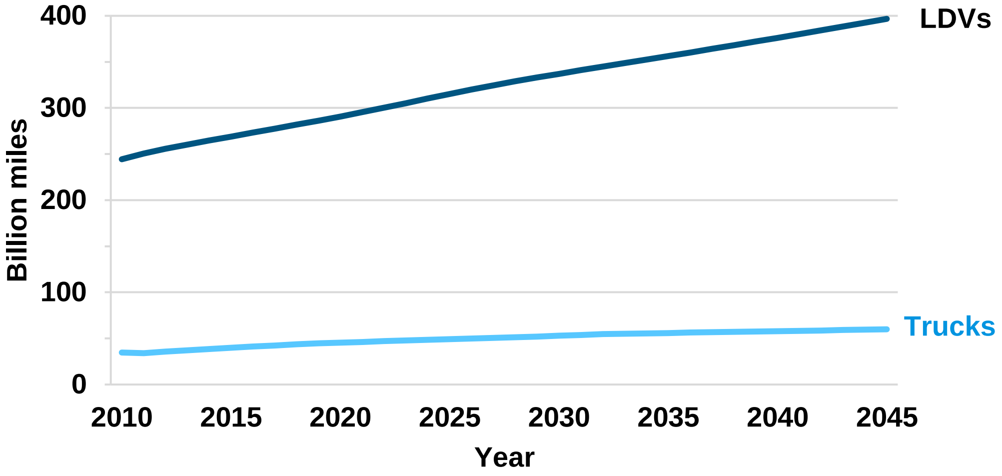


Figure 4.2. Vehicle miles traveled in the BAU scenario. Travel increases steadily for LDVs (60%) and trucks (70%).

The market share of zero emissions vehicles (ZEVs) for each vehicle type is shown in Figure 4.3 below. The sales of ZEV transit buses, per current law, reach 100% of the market by about 2030; ZEV LDVs reach 10% sales share by 2025 (stocks of 1.5 million vehicles), and 20% sales share by 2030 (stocks of about 3 million vehicles). They remain flat thereafter as the market is not assumed to grow without further policies. Nearly all of the ZEV vehicles in this BAU scenario are electric or plug-in hybrid, with a small share that are fuel cell.

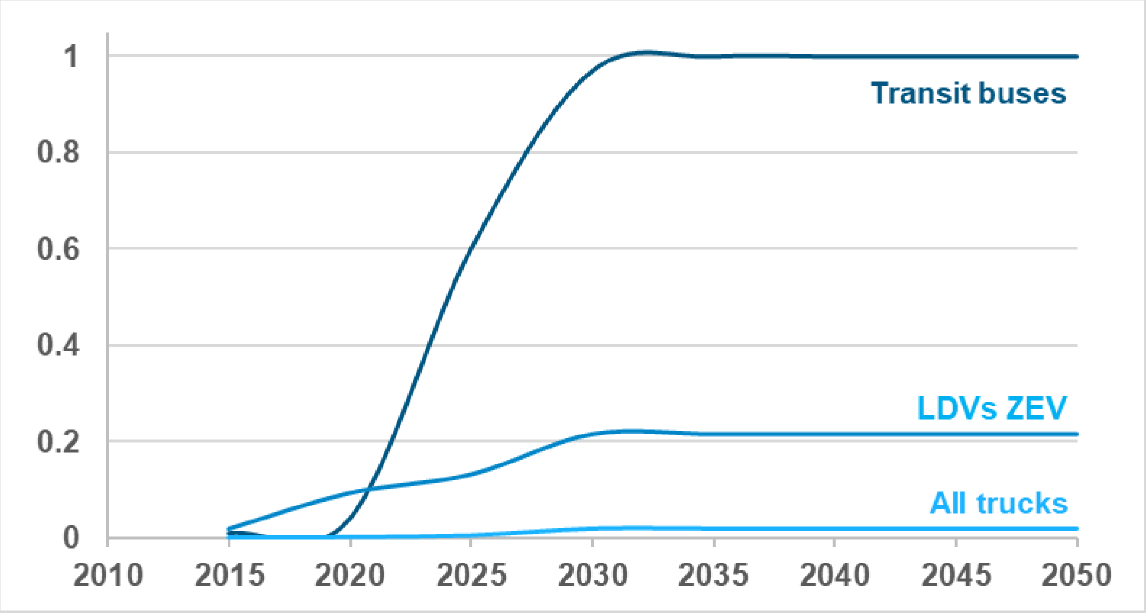


Figure 4.3. Sales shares of zero-emission LDVs, trucks, and buses in the BAU

The net effect of this BAU scenario on road vehicle (car, truck, and bus) energy use is shown in Figure 4.4. Energy use drops mostly due to an improvement in conventional vehicle fuel economy, with only a very small shift toward electricity or hydrogen due to ZEVs. The energy mix for transportation in the state remains predominantly petroleum based.

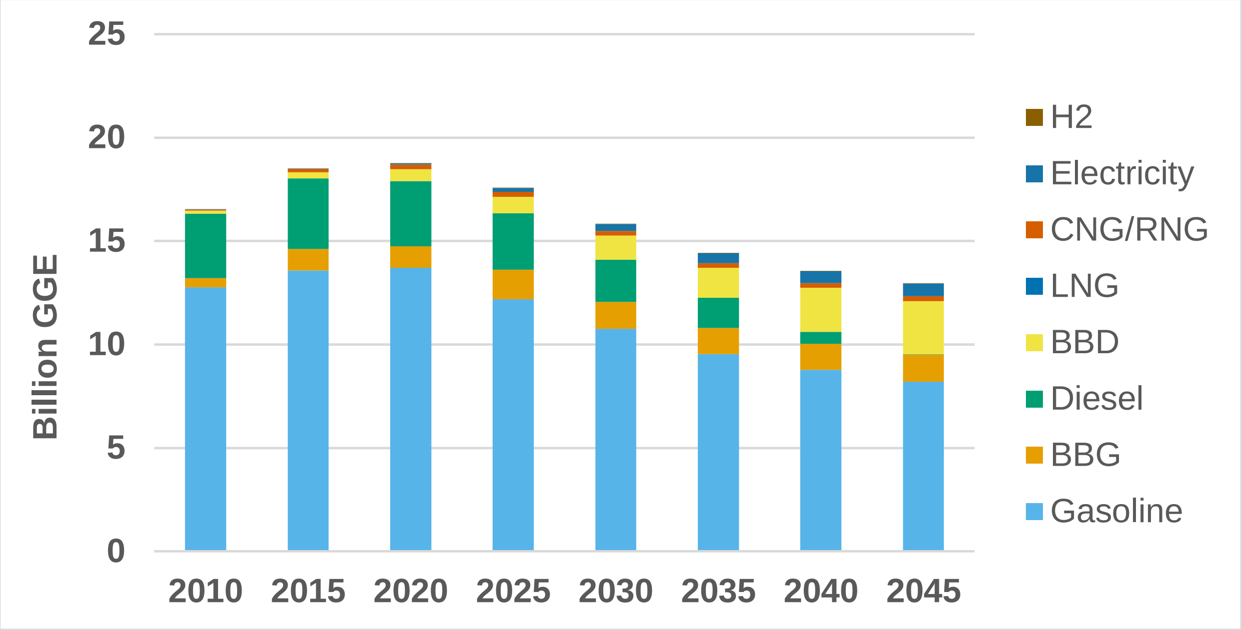


Figure 4.4. Fuel consumption by fuel type in the BAU scenario. The fuel mix in the BAU scenario shifts only modestly towards lower carbon fuels. (H2, hydrogen; CNG/RNG, compressed natural gas/renewable natural gas; LNG, liquefied natural gas; BBD, bio-based diesel; BBG, bio-based gasoline).

Similarly, GHG emissions change in proportion to energy use, with some increase through 2020 and then a slow decline to 2045 (Figure 4.5). The net change compared to 2010 is about 10%.

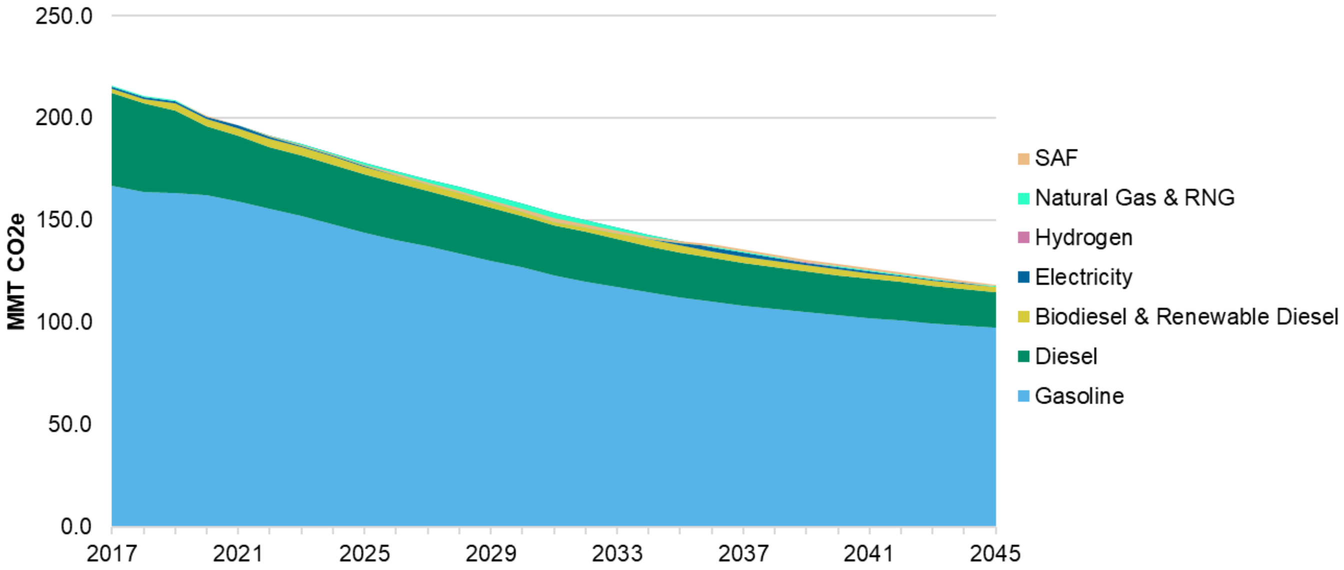


Figure 4.5. Life cycle GHG emissions from Fuels – BAU. Overall GHG emissions in the BAU scenario shrink by about 42% from 2020 to 2045. (SAF, sustainable aviation fuel; RNG, renewable natural gas)

4.1.5 Benchmarking

The most important benchmarking activity in the BAU scenario is to ensure that principal variables are aligned with historical data as presented in EMFAC for 2010–2020. The energy use and other travel indicators have been calibrated in this manner. We have also compared the BAU project to some other projections and found that in general the results are similar, though there is variation across available projections. An example is shown in Figure 4.6 below. All of the more recent projections cited show very similar ZEV LDV stock growth in their BAU scenarios, reaching about 3 million in 2030.

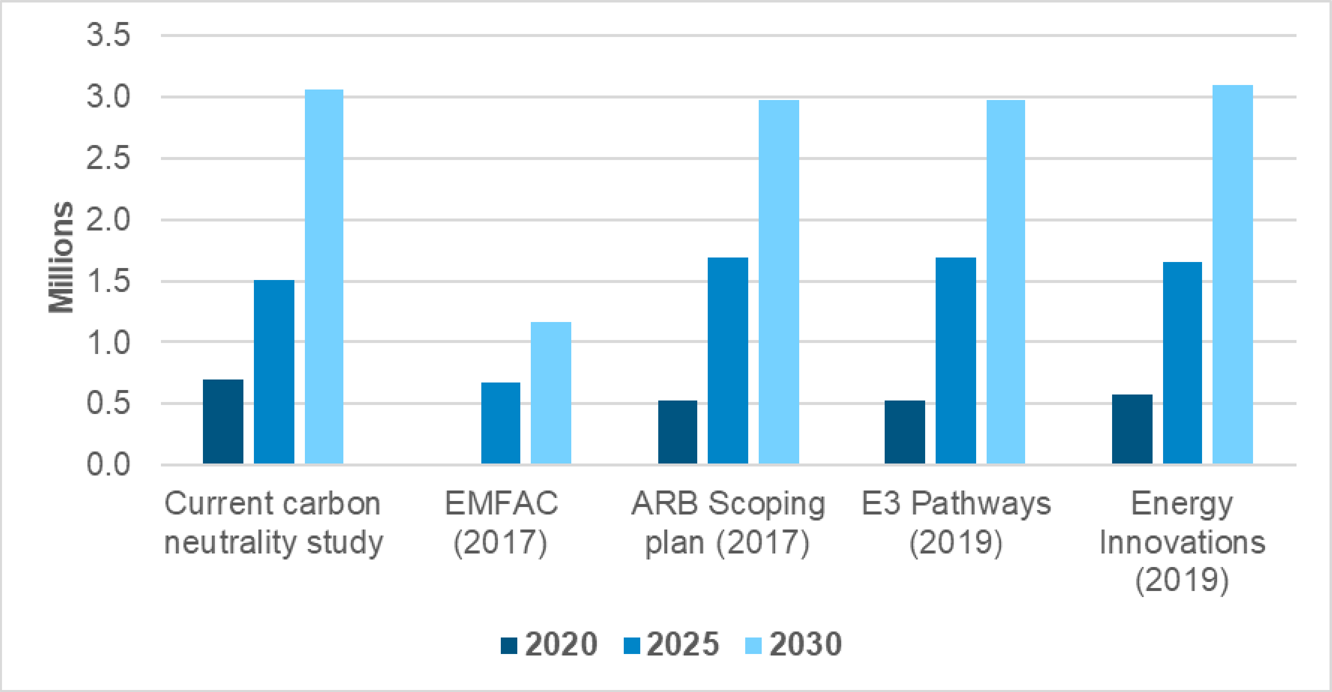


Figure 4.6. Comparison of this study's BAU (bars furthest left) to other prominent BAU studies of the transportation sector for LDV stocks.

4.2 Low Carbon Scenarios

The analysis of achieving a very low-carbon transportation system by 2045 includes the development of a number of scenarios, with a "central low-carbon scenario" or LC1 scenario, and a number of "side cases" (detailed below in under 4.5 Side Cases) that show alternative pathways to reaching the goal. In terms of road vehicles, the LC1 scenario is designed to achieve a near-net-zero CO_2 emissions transportation system by 2045, with a rapid ramp-up in ZEV sales for light-duty vehicles and trucks, reaching 100% ZEV market shares by 2040. It also includes a ramp-up to exclusive use of non-petroleum, low-carbon energy for these ZEVs, and low-carbon fuels for the remaining internal combustion engine vehicles (ICEVs), by 2045. Finally, it includes a 15% reduction in per-capita LDV VMT in 2045 compared to the BAU case. A detailed analysis of the BAU case suggests a 1.8% reduction in per-capita VMT by 2045 that can be expected as a result of changes in land use and the built environment that are expected to occur based on current policy directions. The LC1 scenario then targets a 15% per-capita VMT reduction in 2045 relative to the BAU (which itself achieves a 1.8% reduction relative to 2020). We assess how this can be achieved with a combination of strategies that include changes to the built environment (changes in urban form and land uses, transit expansion, and infrastructure for bicycles, scooters, and e-bicycles), transportation pricing strategies (e.g., fuel and road pricing, parking pricing, and dense urban area cordon pricing), expanded micromobility and active modes, and other VMT related strategies.

Additional side cases of the low-carbon (LC1) scenario have specific departures from these basic assumptions and are described in detail in a following section. These include: a "High ZEV" (HZ) case, with accelerated uptake of LD and M/HD ZEVs; a "High Fuel Cell" (HFC) case, with more FCEVs and fewer BEVs for light-and heavy-duty vehicles, and a “High Liquid Fuels” (HLF) case, with slower ZEV uptake and thus more liquid fuels use (such as biofuels) through 2045.

4.2.1 The Central Low-carbon Scenario (LC1)

This scenario features achieving a near 100% transition to selling ZEVs for cars and trucks by 2040, with buses already mandated to achieve this target in 2030. ZEVs include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCEVs). The shares of these ZEVs have been determined through a combination of model runs (including choice modeling from previous studies) and expert judgement about what may be reasonable shares for different market classes of vehicles that help to meet the needs of those market classes. The ZEV sales shares overall and by market classes are provided in the series of figures below (Figure 4.7, Figure 4.8, Figure 4.9).

The ZEV sales shares shown in Figure 4.7 are similar for LDVs and trucks, though LDVs hit a 50% market share in 2030, while trucks follow the Advanced Clean Truck (ACT) rule and (on average) hit close to 40%. These targets could certainly be different in 2030 while still hitting a near-100% sales share in 2040, but these provide clear interim targets.

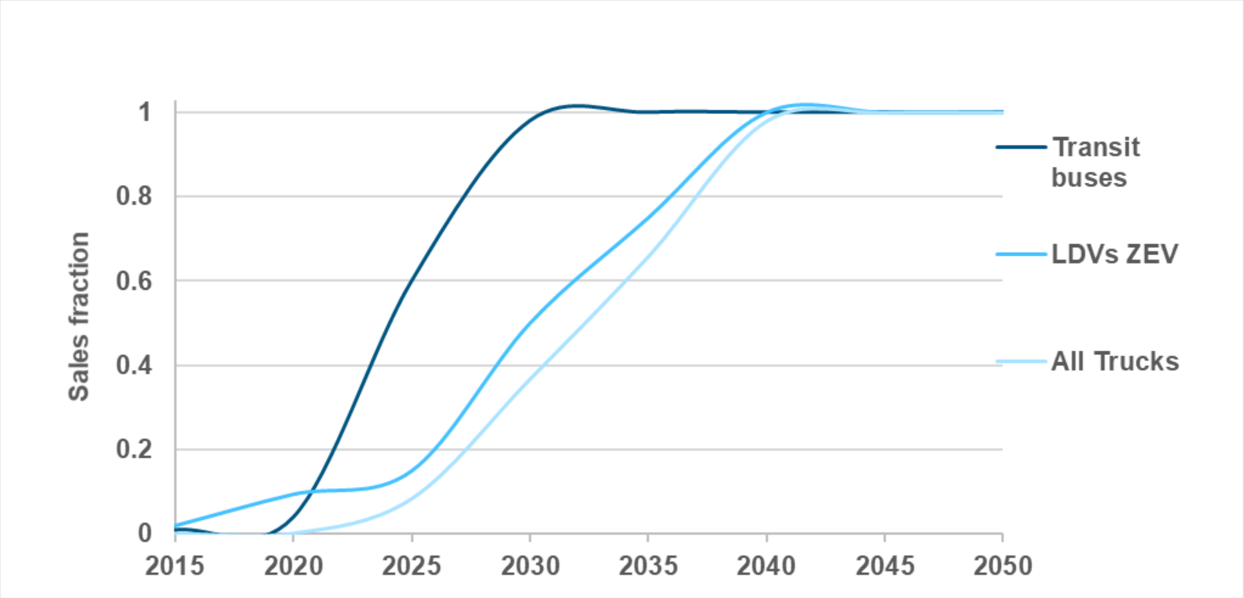


Figure 4.7. ZEV Sales Shares in the LC1 Scenario

For LDVs, the shares of BEVs, FCEVs, and PHEVs are shown in Figure 4.8 below. Particularly after 2025, sales growth is dominated by battery electric vehicles, since these are the lowest cost option of the technologies at that point (see cost analysis). This presumes a strong recharging infrastructure development, as shown in Section 6, Light-duty Vehicle Electrificiation. PHEVs reach about 20% of ZEVs by 2040, while FCEVs reach 15% by 2045.

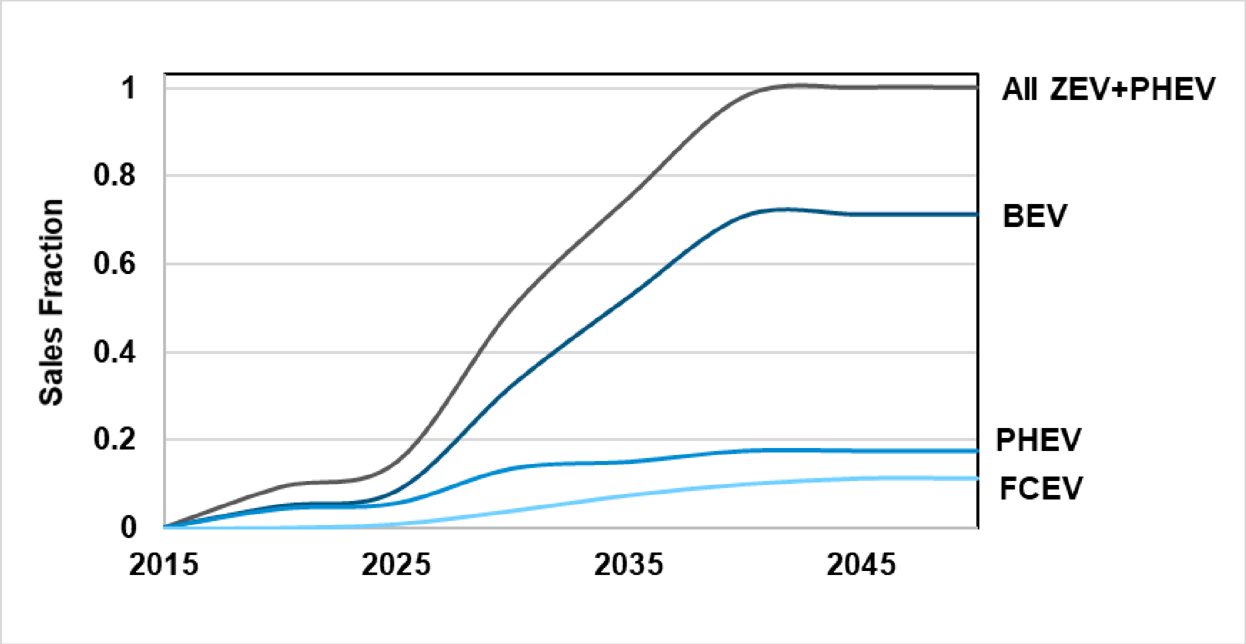


Figure 4.8. Light-duty vehicle (LDV) ZEV sales shares by technology in the LC1 scenario. For LDVs, BEVS dominate but PHEVs reach close to 20% market share and FCEVs close to 15% market share by 2040. Trucks and bus ZEV types vary significantly by market class, but on average reach about 65% BEV and 35% FCEV by 2040. (ZEV, zero emission vehicle; PHEV, plug-in hybrid electric vehicle; BEV, battery electric vehicle; FCEV, fuel cell electric vehicle)

Figure 4.9 shows that sales shares in 2030 and 2045 vary by market segment (with 2 segments for light-duty, 6 for trucks, and 2 for buses). For cars and light-duty trucks, ZEV sales reach 50% by 2030 and 100% by 2045, as described above. For freight trucks, there is a bigger range of ZEV 2030 sales shares, from a low of 30% for heavy-duty trucks and heavy-duty pickup trucks to 100% for transit buses, with other trucks at around 50% ZEV in that year. By 2045 all vehicle types reach 100% ZEV sales shares. The mix of ZEVs also varies with fuel cells playing a relatively minor role for light-duty vehicles and medium-duty trucks, bigger roles for heavy-duty pickups and short-haul heavy duty trucks, and a dominant role for long-haul trucks. The basis for these shares is described further in the LDV and HDV chapters of the report.

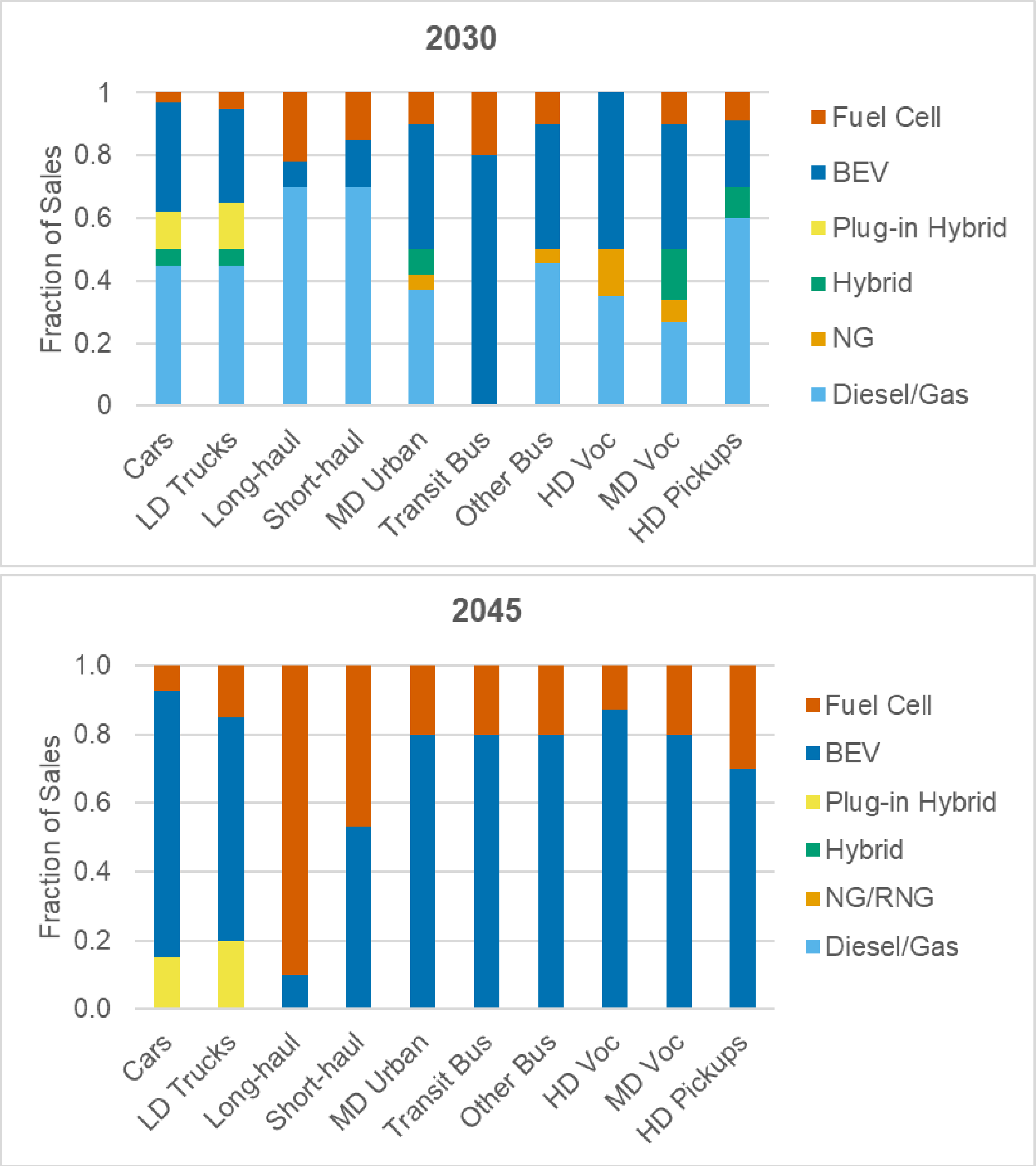


Figure 4.9. Sales shares of LDVs in the LC1 scenario for 2030 and 2045 show a wide variation in shares across vehicle class. by 2045, FCEVs dominate in long-haul and account for half of short haul trucks, while BEVs account for more than 50% sales in all other vehicle classes. (LD, light-duty; MD, medium-duty; HD, heavy-duty; Voc, vocational; BEV, battery electric vehicle; NG, natural gas; RNG, renewable natural gas)

The sales shares were translated into fleet or stock shares of vehicles using the TTM and its stock turnover functions (Figure 4.10). By 2030, ZEVs are a relatively small share of the stock of all vehicle types except transit buses. They reach about 15% stock share of LDVs and less than 15% for all truck types. However, by 2045, ZEVs reach at least 60% share of the stock for all vehicle types, and 80% or more for buses and urban delivery and vocational trucks. If the results were extended to 2050, nearly all vehicles on the road would be ZEV.

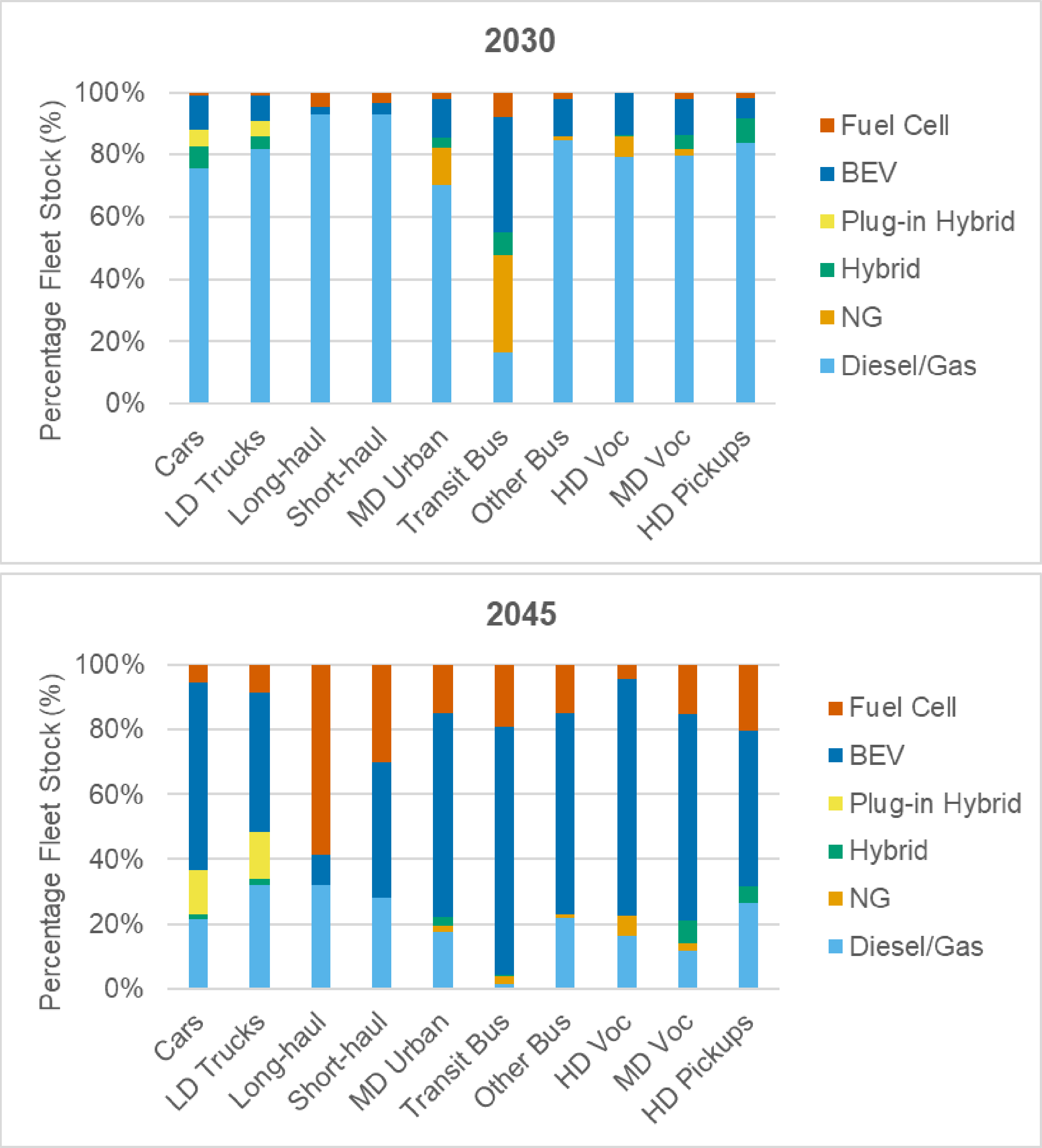


Figure 4.10 Stock shares in the LC1 scenario for the vehicle fleet in 2030 and 2045. Stock shares lag sales shares, with ZEVs reaching no more than 30% of stock by 2030 except for buses. By 2045, ZEVs reach nearly 80% of stock for many classes, but as low as 70% for some, such as long-haul trucking. (LD, light-duty; MD, medium-duty; HD, heavy-duty; Voc, vocational; BEV, battery electric vehicle; NG, natural gas)

The energy use profiles shown in Figure 4.11 take into account the typical levels of annual driving done by different vehicle types and their on-road efficiencies (which also vary considerably by technology and tend to improve over time). This shows fuel use by fuel type, and by year, across all cars, trucks, and buses in the LC1 scenario.

Total road transportation fuel use declines steadily into the future in the LC1 scenario, though all of the decline is in petroleum (gasoline and diesel), while all alternative fuels grow, at least through 2040. Biofuels demand grows the most until about 2030, then electricity dominates increases in energy demand. After 2040, biofuels consumption starts to drop and will be mostly phased out by 2050. Hydrogen demand grows considerably after 2035. Electricity use would grow to even higher levels but is kept in check by the high efficiency of electric vehicles, which use about 0.4 units of energy or every 1 unit of petroleum fuel used by the ICEVs they displace. This contributes to the rapid drop in overall energy use in the scenario.

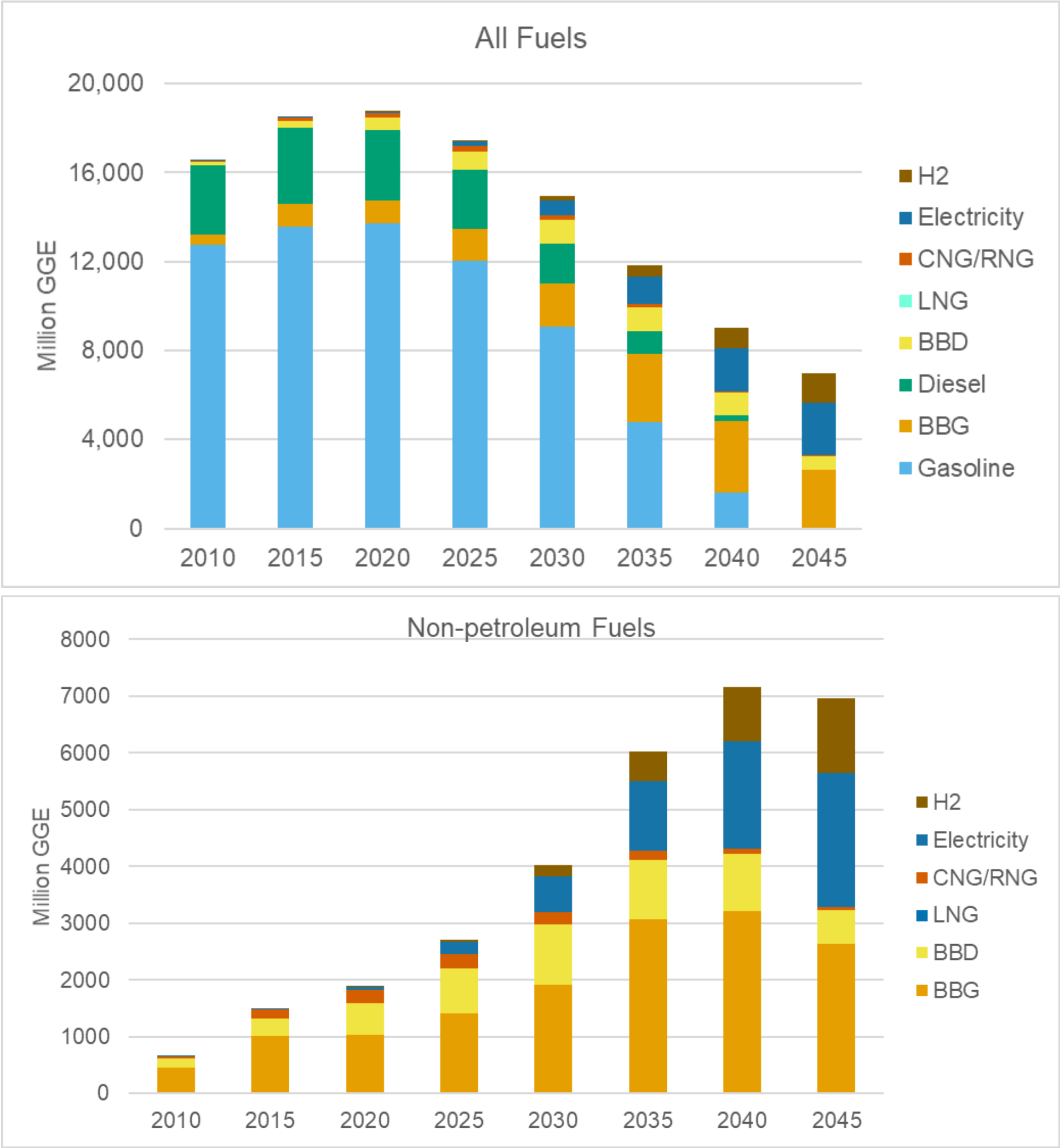


Figure 4.11. Fuel consumption by fuel type in the LC1 scenario for all fuels and non-petroleum fuels. Non-petroleum fuels (electricity, hydrogen and biofuels) dominate by 2040, with about a 50-50 split between electricity/hydrogen vs biofuels by 2045. (BBD, bio-based diesel, including biodiesel and renewable diesel; BBG, bio-based gasoline including ethanol blends and drop-in gasoline replacement fuels; CNG, compressed natural gas; H2, hydrogen; LNG, liquefied natural gas; RNG, renewable natural gas.)

The analysis of this fuel transition is presented in more detail in the fuels chapter.

The result of this transition is a rapid decarbonization of the road transportation sector, as shown in Figure 4.12. CO_2e emissions decline rapidly after 2025, as low-carbon electricity and hydrogen replace petroleum. By the time electricity and hydrogen reach large volumes (after 2030), their well-to-wheel carbon intensities are low enough that they barely register as a source of CO_2e on the figure.

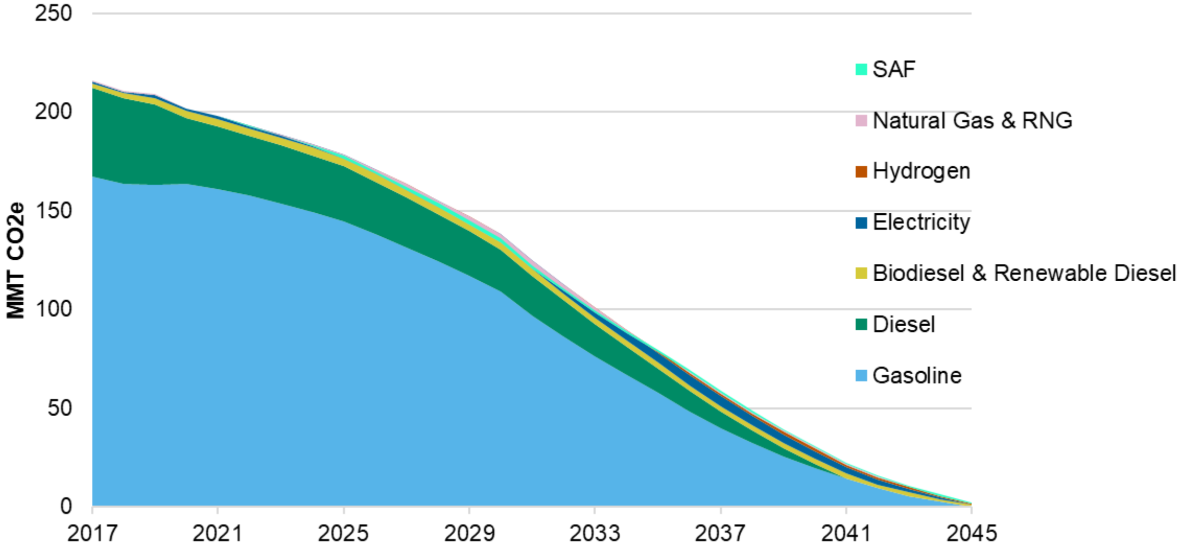


Figure 4.12. GHG emissions in the LC1 scenario. Life cycle CO_2 is close to zero by 2045, with remaining emissions from biofuels, as H2 and electricity related emissions reach nearly zero. (RNG, renewable natural gas; SAF, sustainable aviation fuel)

4.2.1.1 Scenario LC1 Vehicle/Fuel Cost Analysis

The LC1 scenario incurs a range of costs (and provides a range of benefits). Here we focus on the vehicle purchase costs and fuel costs and how these compare to the BAU. These are actually “expenditures,” or amounts spent each year on new vehicles and on fueling all existing vehicles. We do not at this time include maintenance or repair costs, or any policy-related costs such as fuel taxes, the Low Carbon Fuel Standard (LCFS), or various other taxes or subsidies.

Expenditures on vehicles and fuels over time are shown in Figure 4.13, as the difference between those in LC1 and the BAU scenarios annually from 2020-2045. The figure shows vehicle- and fuel-related and total expenditures, for cars, trucks and buses, and all technology types. Vehicle costs are higher in LC1 through the 2020s due to the higher sales of more expensive electric and fuel cell technology vehicles, while fuel costs are lower after 2025, due to the lower cost of electricity used in BEVs and PHEVs (while hydrogen vehicles [FCEVs] do not provide energy cost savings until later). These reach an annual expenditure peak of $2.1 billion more than the BAU around 2027, then drop below the BAU level by 2031. They then become far lower over the course of the 2030s. If costs are not discounted, the cumulative additional costs between 2020 and 2030 are about $10 billion, followed by a savings between 2031 and 2045 of about $177 billion. If future costs and savings are discounted at 4% per year, these amounts drop to $8 billion between 2020 and 2030, and $80 billion in savings from 2031 to 2045.

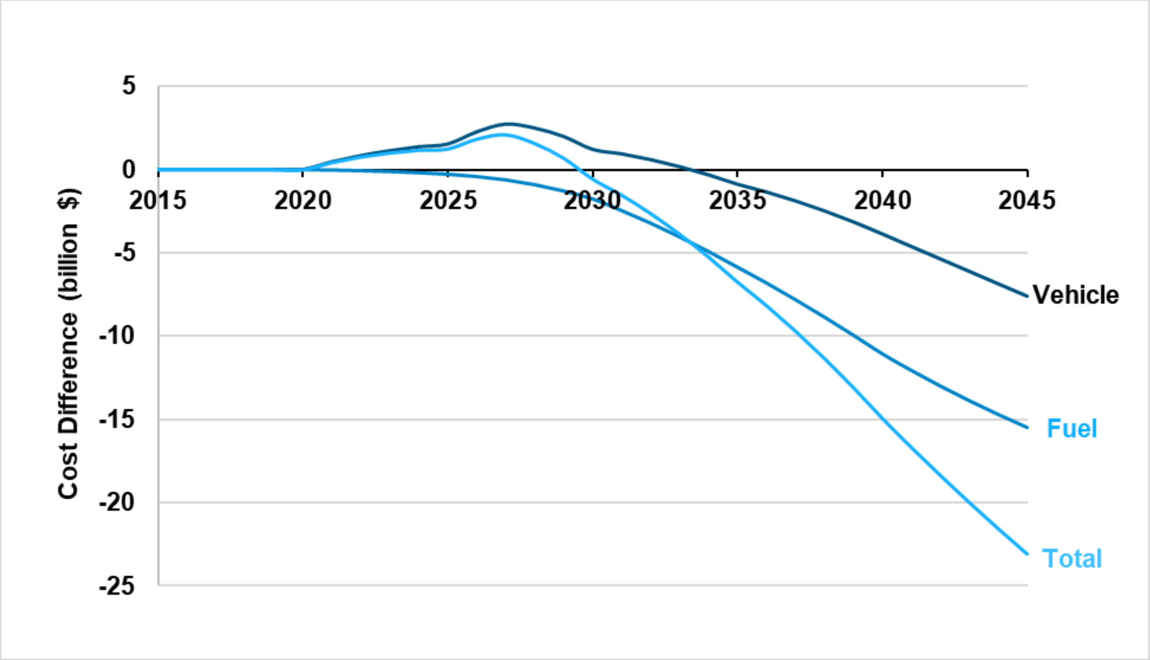


Figure 4.13. Differences between the LC1 and BAU scenarios (i.e., LC1 minus BAU) in expenditures on vehicles and fuels. Higher vehicle purchase costs through 2030 result in a net high expenditure level of around $10B, but after 2030, ZEV vehicle savings on both purchase and fuel cost are lower than in the BAU, resulting in net cost savings of close to $177B from 2030 to 2045.

The incremental costs of LC1 broken out by LDV and truck/bus are shown in Figure 4.14.

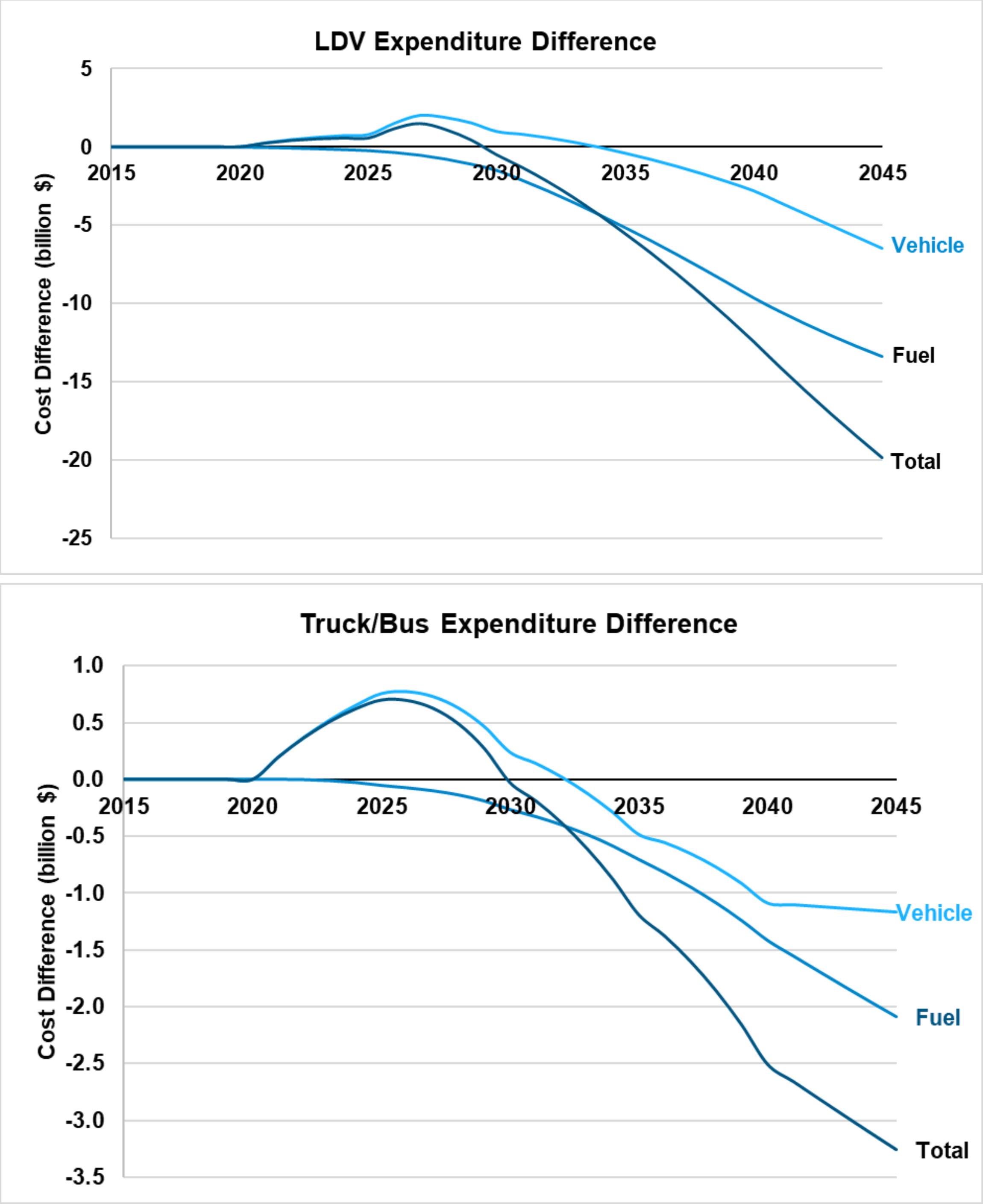


Figure 4.14. Expenditure differences between the LC1 and BAU scenarios (LC1 minus BAU) separated for LDVs (*top*) and trucks/buses (*bottom*). (Note: The y-axis scales differ between panels.) LDV purchase and fuel expenditures are far higher than for trucks, due to the much larger scale of this market, but they drop below zero compared to the BAU in 2030. Both vehicle groups show a steep drop in expenditures after this point. Trucks also use a somewhat greater share of hydrogen than cars do, which is more expensive—but this is not a major factor until after 2030.

Despite the overall lower expenditures in LC1 out to 2045, the net higher expenditures between 2020 and 2030 will present an issue for consumers and in markets in general, in terms of ramping up ZEV car and truck sales. We discuss approaches for dealing with these higher costs in Section 5, Policy Mechanisms.

4.3 Fuels: Life Cycle Emissions

Life cycle GHG emissions from transportation fuels decline between 2020 and 2045 by 42% (to 121.3 MMT) under the BAU scenario but by 98% (to 4.5 MMT) (Figure 4.15). Most of the residual emissions come from biofuel production. Some of these emissions would occur in California, through activities which would be captured in the Greenhouse Gas Inventory, in the industrial or agricultural sectors; others would occur out of state. The residual emissions are significantly less than the plausible maximum carbon capture and sequestration potential identified by Lawrence Livermore National Laboratory in the *Getting to Neutral* report [198], and so may potentially be offset by net-negative CCS projects.

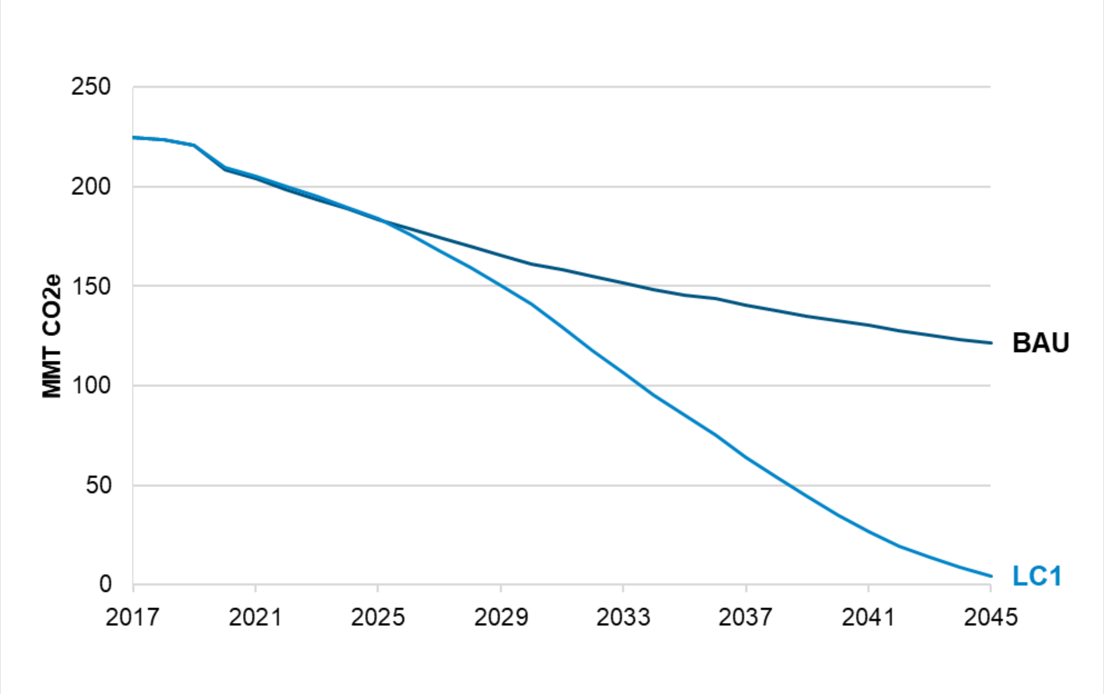


Figure 4.15. Life-Cycle GHG emissions each year from Fuels, in the LC1 and BAU scenarios

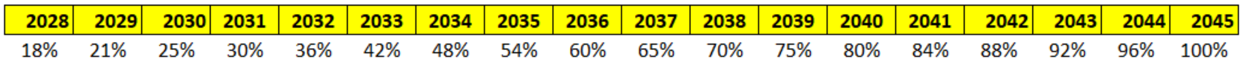
As shown above, the LC1 scenario evaluates the impact of rapid adoption of ZEVs, especially battery electric vehicles, coupled with ambitious deployment of low-carbon alternative fuels for internal combustion engines. While ZEVs dominate the fleet in 2045, there is still a substantial pool of ICEVs, which will continue to demand liquid fuels. These—along with aircraft, marine engines, backup power generation, and other unusual use cases—will maintain demand for several billion gallons per year of low-carbon liquid or gaseous fuels capable of achieving very low carbon intensities by 2045, roughly defined as 5 g CO_2e per megajoule or less. Most of the fuels that would satisfy this demand—while achieving the 2045 carbon neutrality target—rely on technology that has not been commercialized yet, nor studied under real-world conditions at scale.

The LC1 scenario makes the following changes to analytical parameters compared to the BAU:

TTM LC1 fuels consumption outputs were used as the primary input to the fuels model.

- LCFS targets were adjusted to the following trajectory shown in Table 4.2 (see Fuels Policy Implications section for discussion on LCFS targets):

Table 4.2. LCFS targets trajectory from 2027 to 2045



2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
18%	21%	25%	30%	36%	42%	48%	54%	60%	65%	70%	75%	80%	84%	88%	92%	96%	100%

- Light-duty electric vehicle (EV) credits were phased down to zero between 2037 and 2044
- Heavy-duty EV credits were phased down to zero between 2040 and 2044
- More rapid CI reductions from starch ethanol, drop-in gasoline substitutes, and sustainable aviation fuel. This is assumed to be through a combination of improvements in process efficiency, as well as the entrance of new, more advanced fuels over time. This resulted in most drop-in gasoline substitutes reaching 8 g CO_2e/MJ CI by 2045.
- Drop-in gasoline substitutes added. Volumes reach 500 mm gge/year in 2030, peak at just over 2.6 billion gge/year in 2039 and 2040, and fall to 2.4 billion gge/year in 2045 (all volumes exclude renewable naphtha co-product from RD production).
- Net-negative CCS credits entering the market starting in 2030, and rising to 4.5 mmt/year by 2045.

Fuels analysis for LC1, as well as other scenarios which achieve the 2045 carbon neutrality target present three distinct questions:

First: How should California satisfy the primary energy requirements of its transportation system?

Second: What portfolios of plausibly available fuels are capable of satisfying California’s expected transportation demand at net-zero carbon emissions in 2045?

Third: What are the best paths for California to follow to that end state?

Primary energy, as used in the first question, refers to the first form of energy found in nature, which is harnessed and converted into other forms for human use. The transportation system has historically been dominated by fossil fuels, especially petroleum, as the primary energy source. Producing and consuming fossil fuels emits significant amounts of greenhouse gases into the atmosphere. While some emissions can be captured and sequestered or utilized, no technology exists or is likely to exist in the next two decades that can reduce emissions from fossil fuel production, refining, and consumption in internal combustion engine vehicles to a level compatible with carbon neutrality in 2045 at scales that approach current in-state petroleum consumption. Net-negative carbon capture and sequestration projects may provide a modest carbon budget which allows for a minimal amount of fossil fuel consumption in the long run (See: Carbon Capture and Sequestration section in Fuels Policy Discussion), but the majority of primary energy will need to come from non-emitting sources, such as electricity generated by renewable or non-emitting means, or sustainable biomass. At present, most options for producing biomass at the scales needed to displace fossil fuels entail emissions from fertilizer, farm equipment, and conversion to fuels [199]–[202]. Some biofuel pathways can plausibly achieve low enough emissions to contribute to a carbon-neutral portfolio in 2045, though it is highly unlikely there is enough near-zero emission biomass available to allow a simple substitution of biofuels for fossil ones. So, renewable and non-emitting electricity are likely to be the dominant source of primary energy for scenarios that achieve the 2045 carbon neutrality goal.

Knowing the primary energy source informs answers to the second question. Zero-carbon electricity could be conveyed to vehicles as electrical current and stored in batteries, as hydrogen for fuel cells, or as hydrocarbons generated using air, water, and electricity as feedstock. At present, batteries represent the most mature, cost-effective, and scalable approach of these, however alternative technologies continue to evolve. There may be some use cases for which batteries are not suited, so it is too early to categorically exclude other energy carriers from consideration in long-term scenarios.

The third question regarding optimal pathways to reach the zero-net-carbon end state is quite complicated. At present, there is only one binding GHG emission reduction target that affects the transportation system between 2021 and 2045: the SB 32 requirement to reduce emissions 40% below 1990 levels by 2030. This allows some flexibility regarding timing of emission reductions, though it must be noted that the timing of emissions greatly impacts their net effect on climate change [203]. Since climate warming is a function of GHG emissions and time, earlier cuts have a greater impact than later ones, and back-loading emissions cuts to ease the compliance burden may not actually accomplish the state's climate goals even if it nominally complies with emission reduction targets.

Questions about the timing of emissions reductions are particularly salient in the context of low-carbon liquid gasoline substitutes in the mid- to late 2030s in the LC1 scenario.

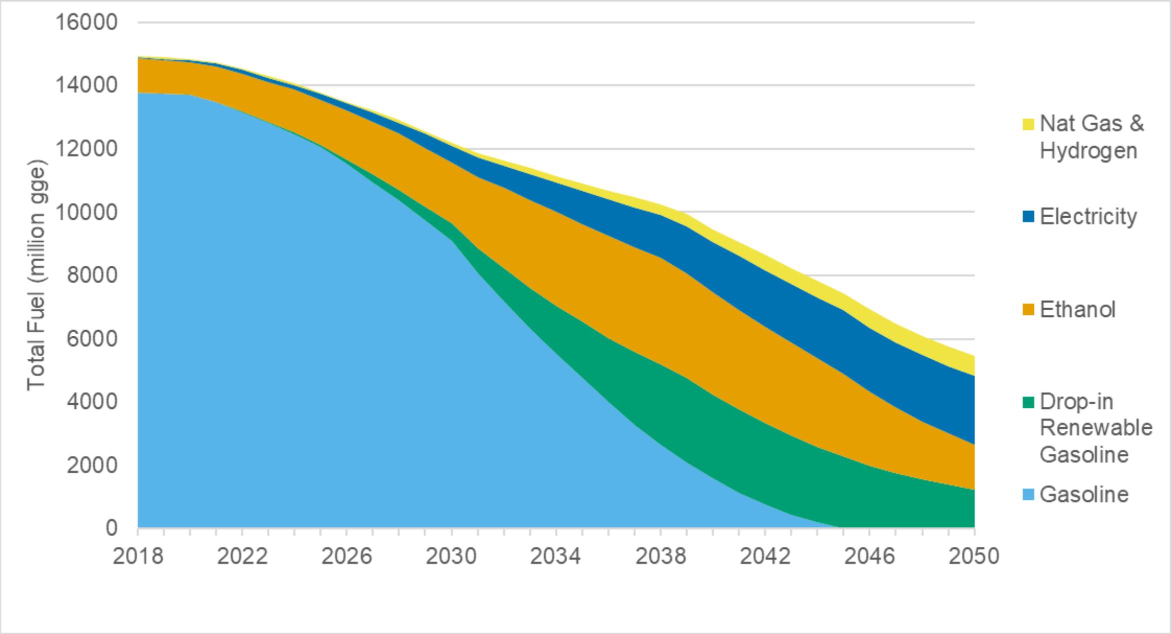


Figure 4.16. Total gasoline and gasoline substitutes each year in the LC1 scenario

Despite rapid deployment of ZEVs, this scenario requires a substantial quantity of liquid fuels, particularly in the gasoline pool, through 2045 (Figure 4.16). Increasing the ethanol blend wall to 15% in 2030 reduces the amount of petroleum consumed in favor of renewable fuels. Since this blend wall increase occurs after aggregate gasoline consumption has begun declining, the increased demand for ethanol does not result in an increase in state-wide aggregate ethanol consumption. It instead approximately returns consumption to the level seen in the early-mid 2020s, though further research is needed to more precisely evaluate supply and demand dynamics. Further blend wall increases may allow more rapid reduction in petroleum consumption, and their associated emissions, though as total liquid gasoline (petroleum and drop-in alternative) there is less of a fuel pool to blend it into. Increasing the blend wall also preserves the market for U.S. ethanol producers, which may encourage the deployment of CCS or other emission-reducing technologies onto existing ethanol production facilities, which may not be cost effective in what would otherwise be a rapidly shrinking market.

To maintain the trajectory of this scenario, a low-carbon, drop-in gasoline substitute must deploy at commercial scales in the mid to late 2020s, reaching 500 million gasoline-equivalent gallons by 2030, peaking around 2.6 billion gallons in 2040, then declining slowly thereafter as the residual internal combustion engine vehicles are retired from the fleet. Earlier and more rapid deployment of ZEVs into the light-duty vehicle fleet would reduce the amount of liquid fuels required (see: ZEV side case). The trajectory of petroleum reduction in the LC1 scenario is somewhat concave, with rapid early displacement of petroleum by drop-in gasoline substitutes followed by a more gradual elimination of the remaining petroleum by 2045.

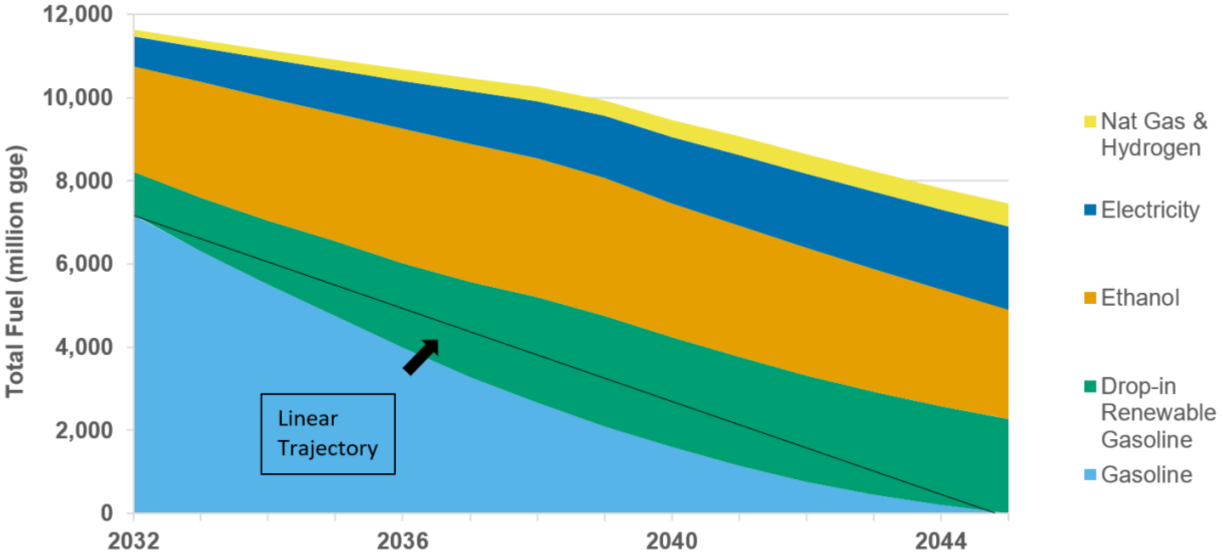


Figure 4.17. Comparison of a linear decline in gasoline consumption to the modeled trajectory in LC1. Additional drop-in gasoline substitutes could reduce emissions during this period, but may not be necessary for 2045 compliance.

A more linear trajectory for petroleum gasoline reduction (Figure 4.17) would reduce the amount of drop-in gasoline substitutes required by as much as 600 million gasoline-equivalent gallons at peak, but delays reduction in petroleum gasoline volumes and significantly complicates LCFS compliance in the late 2030s and early 2040s (See Fuels Policy section for deeper discussion). Further study on the likely development trajectory of gasoline substitutes is needed to better understand the trade-offs between these choices.

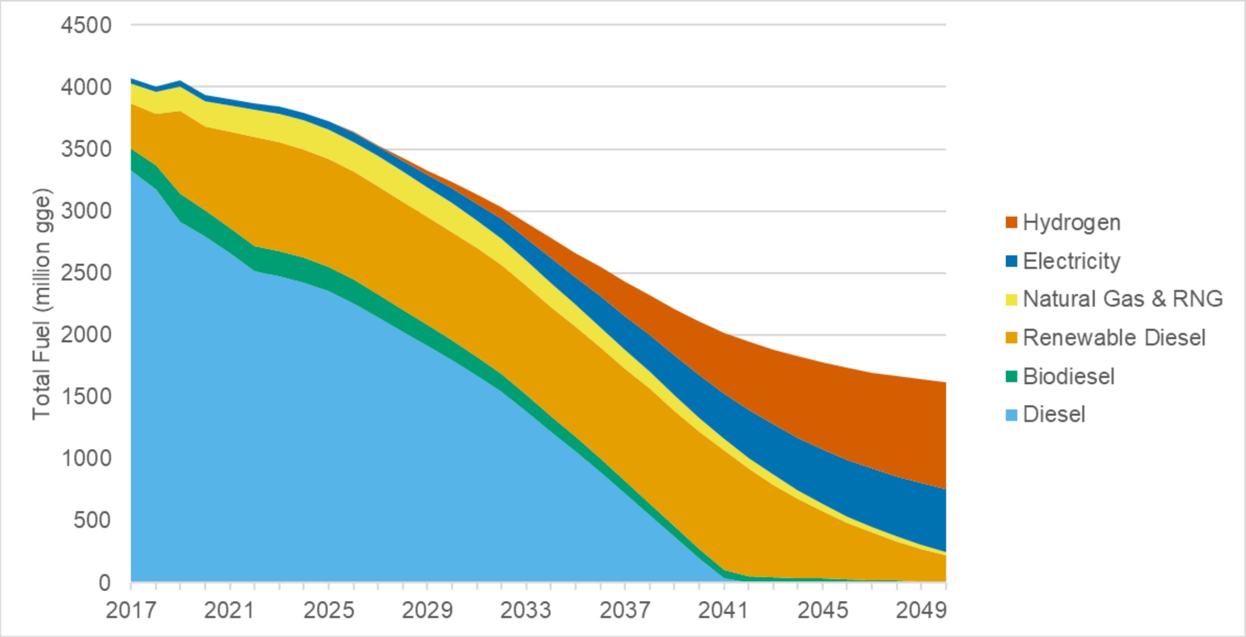


Figure 4.18. Total diesel and diesel substitutes in the LC1 scenario out to 2050

Reductions in petroleum diesel in the LC1 scenario are rapid and less dependent on the emergence of novel forms of drop-in substitute fuels (Figure 4.18). By 2041, essentially all petroleum diesel has been displaced from the system, by a combination of renewable diesel, RNG, electricity and hydrogen. Effort may be required to ensure that the renewable diesel and hydrogen in the system by the late 2030s are of low enough carbon intensity to avoid excess emissions and challenges complying with rapidly accelerating LCFS targets.

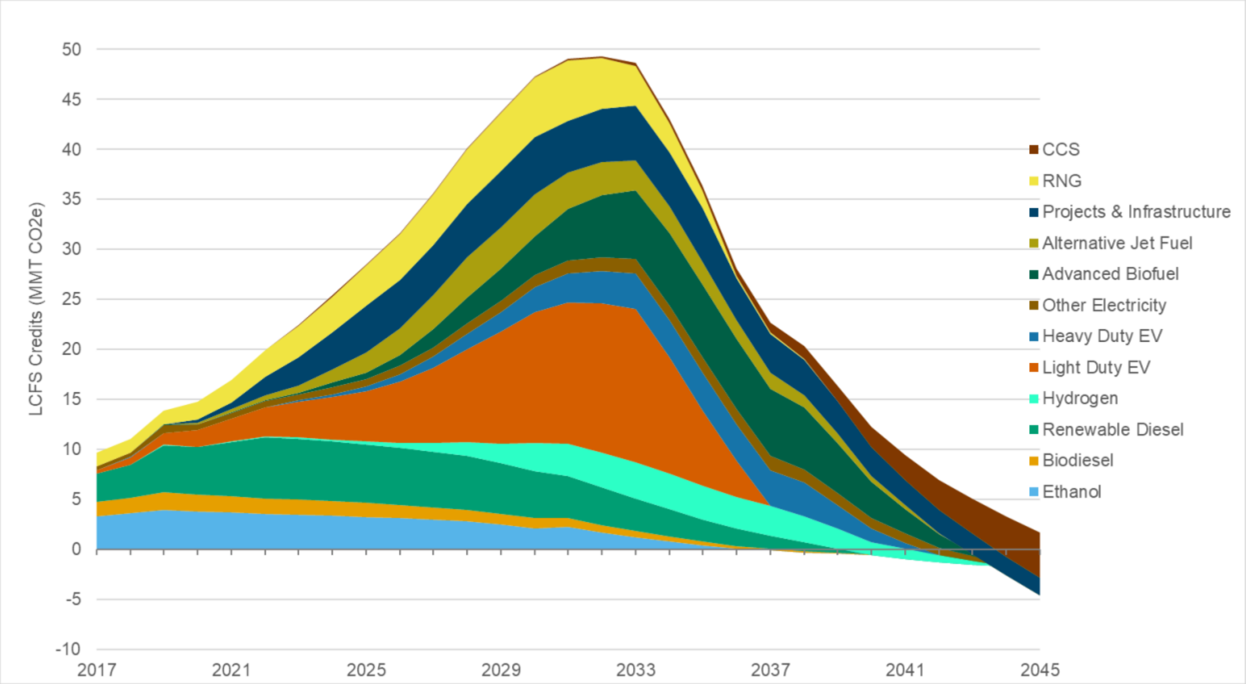


Figure 4.19. LCFS credit generation by fuel category in the LC1 scenario

LCFS compliance under this trajectory exemplifies the challenges of rapid decarbonization (Figure 4.19, Figure 4.20). The rapid deployment of ZEVs and alternative fuels through 2030 would likely generate a significant surplus of LCFS credits under the existing target trajectory, which reaches a 20% CI reduction in 2030. The LC1 scenario models a fleet with almost 5.3 million ZEVs in 2030, coupled with other alternative fuels and demand reduction measures. The combined effect of this would significantly over-comply with the 20% LCFS target, resulting in a rapid accumulation of banked credits and a reduction in LCFS credit price. Given the need to rapidly decarbonize after 2030, in essence going from a 20% target to a 100% target, early compliance and strong incentives for decarbonization will reduce the costs and disruption needed to achieve the 2045 target. In the LC1 scenario, the LCFS targets were adjusted upwards starting in 2027 and reaching a 25% CI reduction target in 2030. This target, as well as the vehicle and fuel portfolio which complies with it approximately matches the "Accelerated Progress" scenario in the *California's Clean Fuel Future* report [204]. After 2030, the LCFS target accelerates rapidly, going from 25% to 80% by 2040, with slightly higher yearly increases in early years. After 2040, the target increases by 4% per year until the average carbon intensity of California fuels is zero.

Even under these ambitious targets, EVs generate massive amounts of LCFS credits and as the fleet progresses in its transition from petroleum fueled ICEVs to ZEVs, there is a risk that EVs will generate enough credits to accumulate an extremely large aggregate credit bank, which would likely depress the LCFS credit price and mute the incentive needed to support the deployment of additional fuels. To counteract this, credit generation from light duty EVs was phased down to zero from 2037 to 2044, and heavy duty EVs phased down to zero from 2040 to 2044. See the Fuels Policy section for more discussion on this subject. Further research is warranted to evaluate the impact of different phase-down mechanisms and schedules.

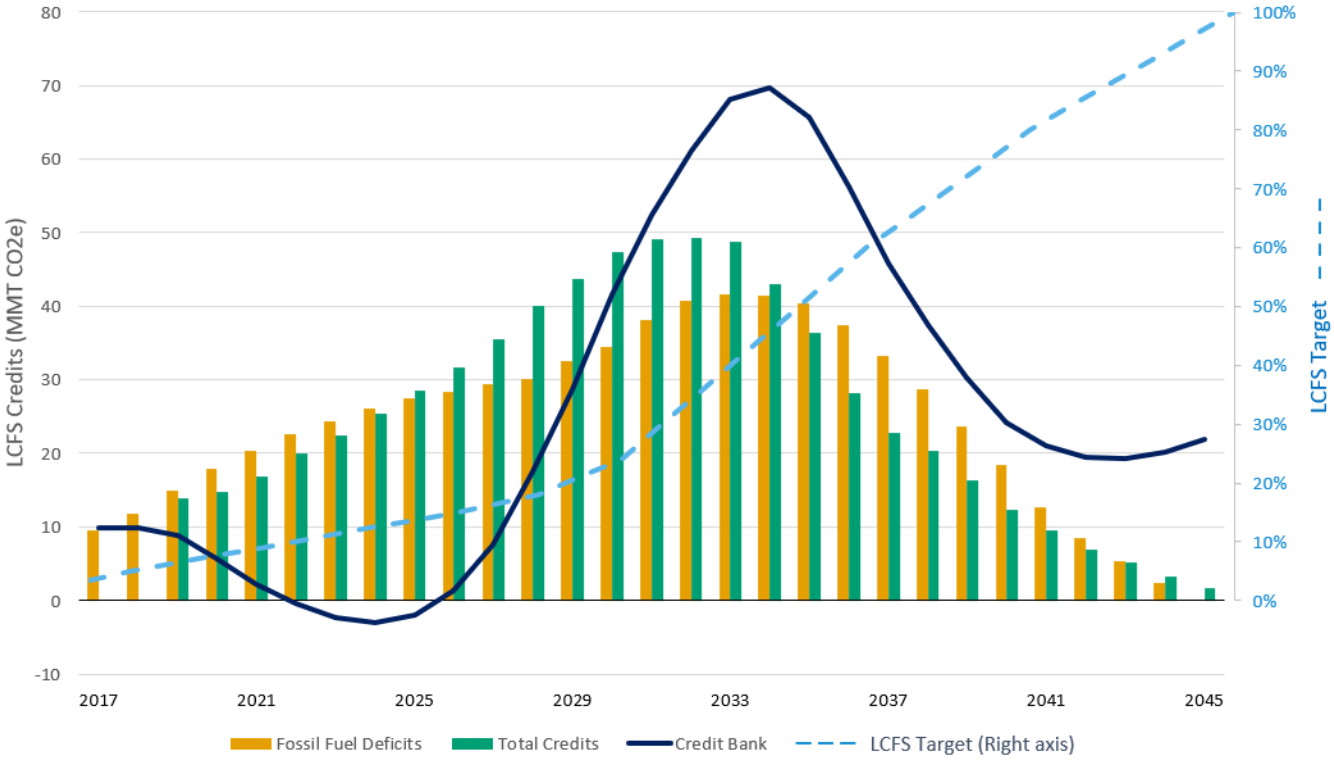


Figure 4.20. LCFS credit balance in the LC1 scenario

Compliance with the LCFS post-2040 is a challenge, as rapidly declining CI targets erode the ability of almost every fuel—except electricity, and electrolytic hydrogen—from a zero-carbon grid to generate LCFS credits. In this scenario, participants in the LCFS program accumulate a substantial bank of credits in the late 2020s and early 2030s, then gradually draw it down through 2045. To avoid deeply negative LCFS credit balances, virtually all alternative fuels consumed after 2040 need to be significantly below 20 g CO_2e/MJ carbon intensity, and likely below 5 g CO_2e/MJ by 2045. In the final years of the program, the LCFS essentially becomes a requirement to offset emissions via CCS projects, since few fuels are sufficiently below the compliance target to generate a significant amount of credits.[13]

CCS, other than that which reduces the carbon intensity of transportation fuels consumed in California, was not explicitly modeled in this scenario due to the uncertainty around the technology and assignment of the carbon budget they would allow to different sectors of the economy. Assuming the deployment of CCS capacity sufficient to generate 2 million additional LCFS credits per year by 2045 largely resolves the problem of negative net balances.

Given the immature state of advanced biofuel production, there is minimal data with which to inform estimates of the investment required for alternative fuels. Some commercial-scale demonstration projects are under

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[13] In this case, "offset" is used to indicate a proportional amount of carbon sequestration through approved LCFS pathways, not projects that reduce emissions pursuant to the Compliance Offset Protocol, which are used in the Cap and Trade program.

construction and should begin production shortly. Some analyses have suggested potential profitability for a mature industry—the "nth plant"—at least with modest policy incentives [205]–[207]. A recent review of the techno-economic analysis literature for nth plant found production cost estimates for several prominent conversion technologies—cellulosic ethanol, biomass-to-liquid (gasification and Fischer Tropsch process), and fast pyrolysis followed by hydrotreatment—to average at or below $4/gge (gasoline-gallon equivalent); see Figure 4.21.

None of these technologies is yet established at commercial scale, in contrast to another technology, HEFA (hydrogenated esters and fatty acids) renewable diesel, which has found profitability and considerable commercial expansion with similar average production cost ($3.70/gge) under existing policy incentives. In most cases, capital expenditure is a comparatively small fraction of levelized fuel costs, and typically integrated into the final cost of delivered fuel.

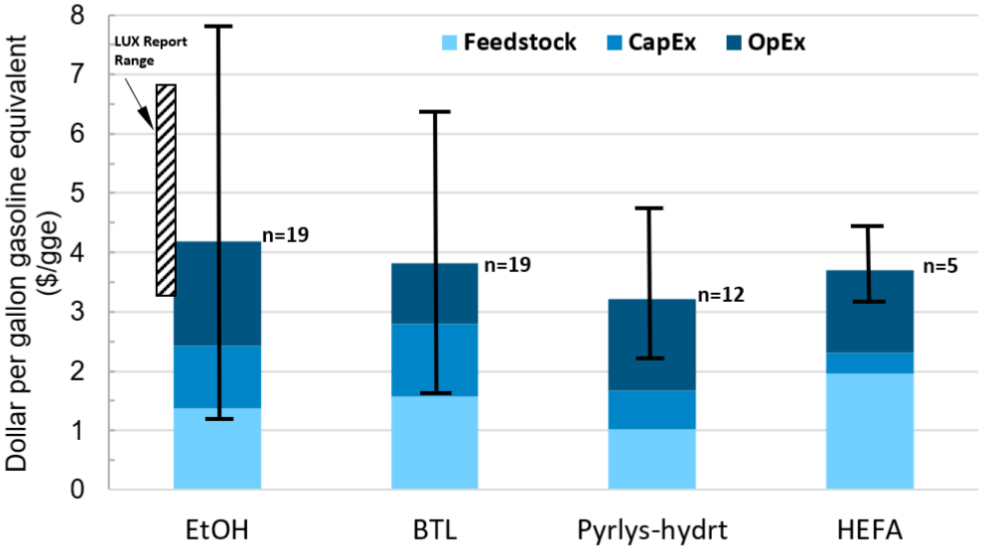

Figure 4.21. Cellulosic and residual oil biofuel costs, average and range from techno-economic analysis literature [206]. (OpEx, operating expenses; CapEx, capital expenses; LUX, Lux Research [a company]; EtOH, cellulosic ethanol; BTL, Biomass to liquid hydrocarbons [gasification - Fishcer Tropsch]; Pyrlys-hydrt, Pyrolysis-to-biocrude then hydrotreatment; HEFA, hydrogenated esters and fatty esters).

The estimates point to pyrolysis having the lowest average production cost among the non-commercial fuels ($3.25/gge), but the wide range of estimates and lack of practical large-scale experience with the technologies makes this assessment not definitive. Moreover, adjusting the analysis to estimate first-of-a-kind pioneer plants, with higher capital costs and lower production facilities, move the first-wave cellulosic biorefinery more definitively out of the range of profitability, without more substantial and sustained policy incentives. A recent study synthesizing a range of technoeconomic analysis studies determined that production costs of drop-in cellulosic biofuels were approximately double those of fossil fuels, or ~$5–6/gallon [208]. A separate analysis of cellulosic ethanol concluded that the industry continues to stagnate under high production costs and a range of technical and non-technical barriers, including difficulty in financing projects and lack of sustained, certain policy signal [209]. A takeaway from these studies is that widespread commercialization of cellulosic biofuels will remain elusive over the next decade, and will likely require significant policy support. The LCFS will provide a strong incentive for this development, but it is uncertain at this point whether it will be sufficient. The track record of challenges within the advanced biofuel space suggest that additional policy support may be required to bring the first wave of commercial scale plants online, however there is evidence that as the industry scales up, prices should come down to the point where the LCFS incentive allows them to be cost-competitive. Additional research is required to better characterize this relationship.[14]

4.4 Benchmarking Milestones

Benchmarking the progress of the fuel portfolio is difficult because fuel consumption is determined by the transition of the vehicle fleet to more efficient, lower-emission vehicles and the travel demand of Californians. The fuels analysis in this report was conducted with the intent that all fuel demands will be met, rationing or price-driven reduction strategies are not part of the compliance portfolio, in order to minimize the risk of regressive impacts. As such, most of the critical benchmarks for progress in the fuels space are largely proxies for reduction in aggregate travel demand, or the transition to ZEVs. Still, there are a few key benchmarks that can help evaluate the state's progress towards its long term goals.

4.4.1 Aggregate Non-Petroleum Fuel Consumption Exceeding Petroleum

Under the LC1 scenario, total transportation energy from non-petroleum fuels exceeds that from petroleum fuels by approximately 2033, plus or minus a year in other scenarios. Delaying the transition to 100% ZEV sales beyond 2035 could prevent the state from achieving the 2045 carbon neutrality target. However, this relationship between the year of attaining 100% ZEVs and attaining 2045 carbon neutrality will also depend on the ability to use advanced biofuels to compensate for a lower percentage of ZEVs.

4.4.2 LCFS Compliance

See the Fuels Policy section for a deeper discussion of LCFS dynamics and options for additional policy support for critical fuels. In general, compliance with the LCFS will continue to be a metric that indicates the state is on course to achieve its 2045 target, provided that the LCFS target trajectory is set sufficiently high to support significant investments in the fuels space. After 2035, the LCFS will likely require significant amendments, but assuming these can be adopted, the program should still be a useful metric for assessing the overall progress towards a decarbonized transportation system.

4.4.3 Low Carbon Liquid Fuel Supply

Under all the LC1 scenario, and all the side cases that achieve the 2045 carbon neutrality target, there is a significant demand for gasoline through 2045, in excess of 2 billion gallons per year, in addition to the roughly 600 million gallons per year of sustainable aviation fuel required for projected intra-state flights (which is assumed to come from waste oils and other existing sources) and smaller volumes for specialized uses. Most of

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[14] UC Davis Policy Institute researchers, led by Drs. Murphy and Witcover are currently developing a model of the LCFS credit market which, when complete, may offer a better evaluation of the need for additional policy support.

this demand will occur in the gasoline pool and require advanced, very-low-carbon fuels to avoid compromising progress toward decarbonization targets. These fuels will need to possess the following characteristics (see Fuels Policy section for a deeper discussion):

- Is compatible with existing spark-ignition engines, without voiding the warranty or compromising performance.
- Has a life cycle carbon intensity below a critical threshold, e.g., 20 g CO_2e/MJ on a well-to-wheels basis.
- Has the capacity to have a carbon intensity low enough meet long-term decarbonization targets, e.g., 7 g CO_2e/MJ or less by 2045.
- Does not increase the emissions of criteria pollutants, toxic air contaminants, or any other pollutant.
- Meets strict sustainability criteria, with minimal indirect land use change impacts.

Based on the modeling conducted for this report, we anticipate that California will need approximately **500 million gallons per year by 2030** of fuels that meet this criteria, and **2 billion gallons per year by 2040**.

4.5 Side Cases

In addition to the main LC1 scenario, we undertook analysis of three "side cases" with different pathways considered to reach a very low carbon transportation system by 2045.

These side cases were selected to try to capture a range of alternative potential pathways that are judged to be reasonable for consideration by policy makers. All come with significant challenges. Comparing these scenarios can provide some insights about: needed progress by specific dates, such as by 2025 and 2030; amounts of vehicles and fuels needed; and the possible costs of undertaking the pathway.

The three side cases are:

- "High ZEV" (HZ) scenario: accelerated uptake of LD and HD ZEVs
- "High Fuel Cell (HFC) scenario, with more FCEVs and fewer BEVs among HD and LD vehicles
- "High Liquid Fuels" (HLF) scenario, with slower ZEV uptake and thus more liquid fuels use through 2045

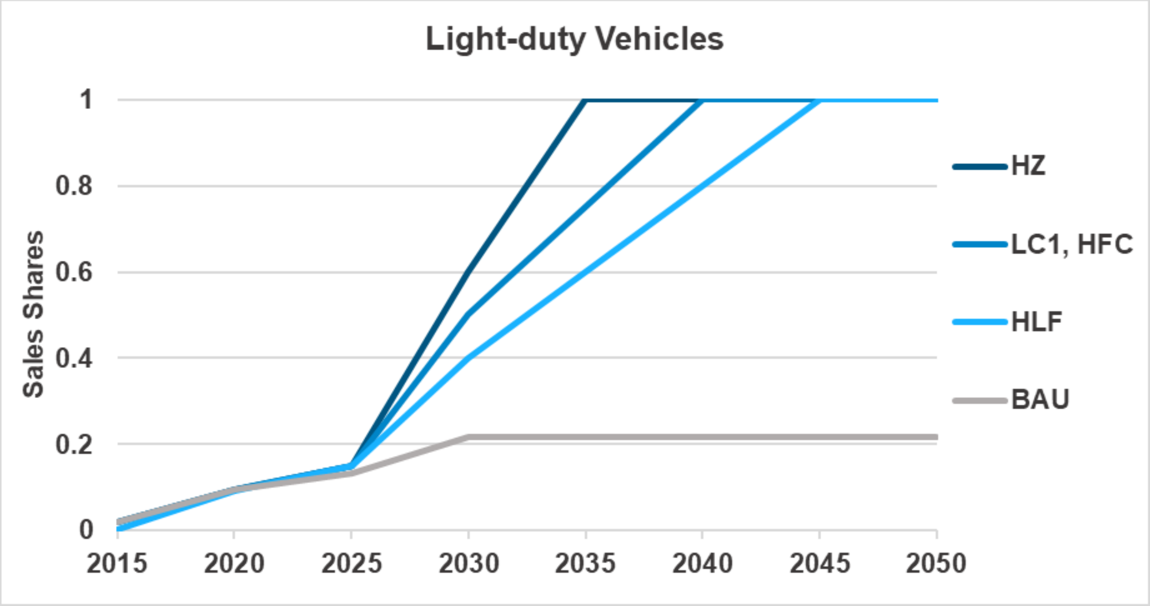
The cases are compared in Table 4.3.

Table 4.3. LC1 and side cases for road vehicles

	LDV (ZEV sales hit 100% by)	Trucks (ZEV sales hit 100% by)	Fuels (100% low-carbon fuels by)	VMT reduction in 2045 vs BAU
LC1	2040	2040	2045	15%
High ZEV (HZ)	2035	2035	2045 (but less needed)	15%
High Fuel-cell (HFC)	2040 (lower BEV)	2040 (lower BEV)	2045 (same as LC1)	15%
High Liquid Fuel (HLF)	2045	2045 (except 2050 for long haul trucks)	2045 (but more needed)	15%

Overall, these side cases differ from LC1 by: (a) the rate of LDV and HDV ZEV penetration into the market, (b) the ratio of electric vehicles to fuel cell vehicles, and (c) the level and nature of changes in vehicle and passenger travel in the scenario.

Figure 4.22 shows the differences in ZEV market penetration over time, across several scenarios for LDV and HDV sectors. The LC1 and “High Fuel Cell” (HFC) scenario follow the same penetration paths for ZEVs as a group, with the HFC having a higher share of fuel cells and lower BEV shares than LC1. The High ZEV (HZ) scenario has a faster rate of ZEV penetration than LC1 and more closely matches the recent Executive Order on ZEV targets in California. The High Liquid Fuels (HLF) case has slower ZEV penetration rates, with LDVs and most truck types reaching 100% in 2045 and long-haul trucks reaching 100% by 2050.



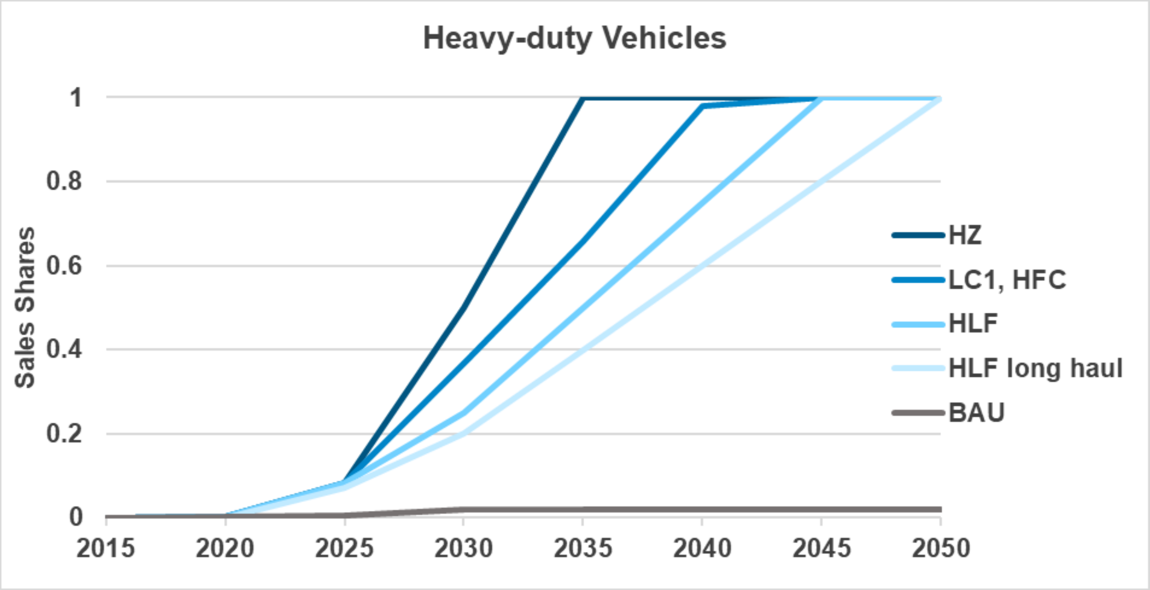


Figure 4.22. LDV (*top*) and HDV (*bottom*) sales shares by side case. For LDVs, ZEV sales shares reach 100% by 2035 in the High Zev case, by 2040 in LC1, and 2045 in the High Liquid Fuels case. For trucks, the target dates are similar except for long-haul trucks in the High Liquid Fuels case, which hit 100% ZEVs in 2050. (HZ, high ZEV case; HFC, high fuel case; HLF, high liquid fuel case; BAU, business as usual)

The difference in fuel cell vehicle sales shares in the High Fuel Cell (HFC) side case compared to LC1 is shown in Figure 4.23. For most vehicle types, the fuel cell market share by 2045 in HFC is twice as high as in LC1, reaching 30% for LDVs and 40% for truck types where it had been 15% and 20% in LC1, respectively. Long-haul trucks increase from 90% to 100% market share, and short-haul trucks increase from 50% to 70%.

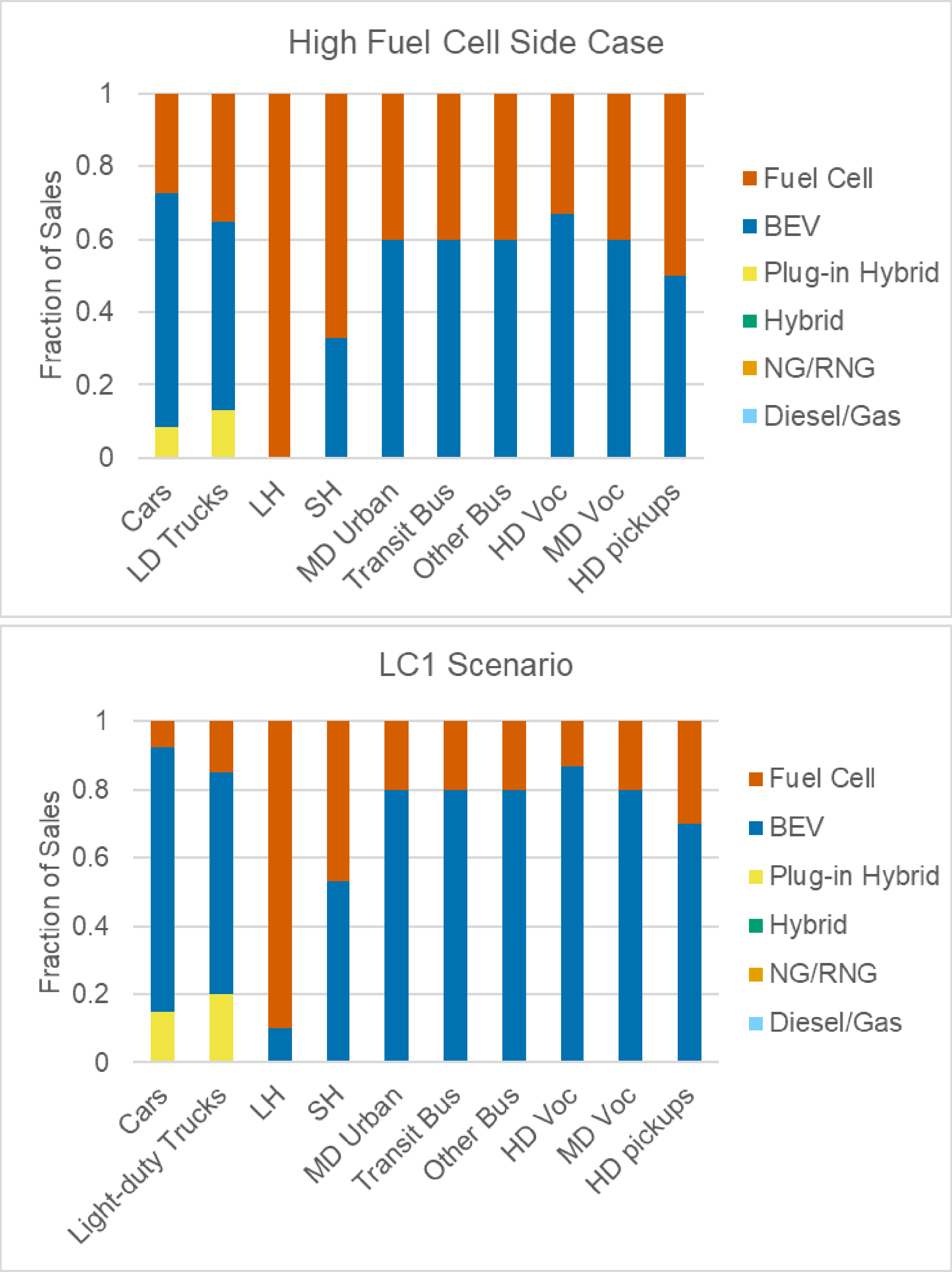


Figure 4.23. Sales shares in 2045 by technology and market class for the High Fuel Cell side case (*top*) and LC1 scenario (*bottom*). In the High Fuel Cell case by 2045, FCEV sales shares are typically 15–20 percentage points higher than in LC1, with BEVs commensurately lower.

Finally, we highlight in Figure 4.24 differences for actual light-duty vehicles sales across the scenarios. We focus on the 2025–2035 period, which highlights differences in the early sales ramp-ups. BEVs/PHEVs range from around 750k to 1.25m sales per year by 2030, compared to around 400k in 2025. For FCEVs, there is a range of about 40k to 100k sales in 2030 relative to about 20k in 2025. Clearly, even in the high liquids case, the ramp-up of these various types of ZEVs is faster than in the BAU.

For BEV/PHEV LDVs, as the market share reaches 100%, the total sales begin to slowly decline since total LDV sales decline slowly, and because they start to lose some market share to FCEVs. On the FCEV side, this is not a concern given their longer phase-in time. It is also notable that FCEV LDV sales in the high fuel cell (HFC) scenario eventually reach more than twice that in the other scenarios.

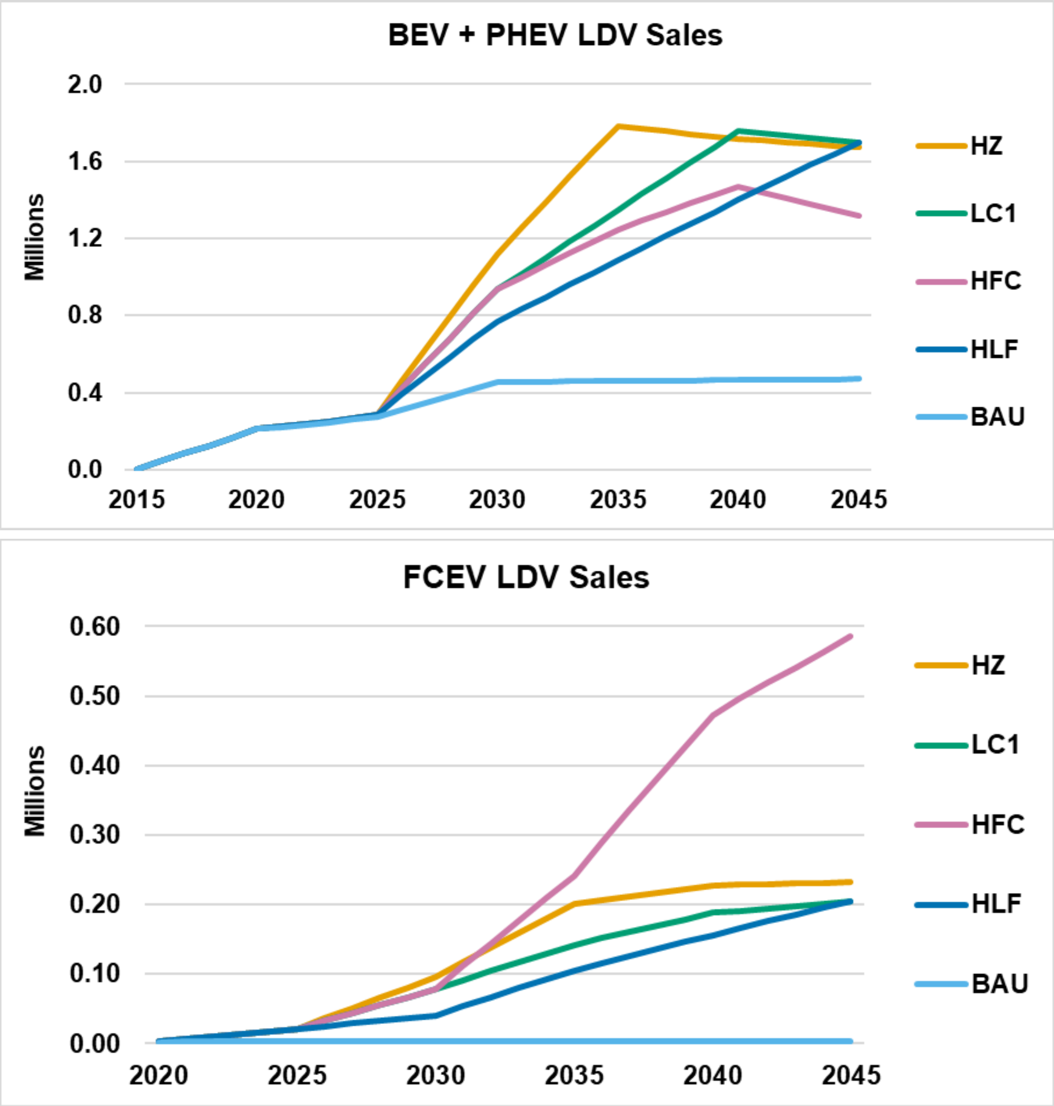


Figure 4.24. BEV/PHEV and FCEV sales by side case through 2045. (Note the y-axes are on different scales.) The ramp-up for BEVs is very steep after 2025, particularly in the HZ scenario; for FCEVs, there is a significant increase, but by far the biggest ramp-up is from 2035 in the HFC scenario.

The changes in vehicle stocks and travel in these side cases is presented in an appendix. Below we show the impacts on fuel use in Figure 4.25. The top left panel shows total fuel use by fuel type in 2030 and 2045 for the LC1 and three side cases and the BAU. The lower left panel zooms in on the four main types of fuel used in these scenarios in 2045: bio-based gasoline, bio-based diesel, electricity, and hydrogen. Finally, a third figure focuses on electricity and hydrogen use in 2035 and 2045 in the different scenarios.

Some observations on these figures:

- As expected, the High ZEV (HZ) scenario uses more electricity and hydrogen, and less biofuel, than LC1. It also uses the least energy overall, while high liquid fuels (HLF) uses the most.
- The High Fuel cell (HFC) case uses the most hydrogen, and the HLF case uses the most biofuel.
- In 2045 for the HLF scenario, bio-based diesel (BBD) is nearly 100% higher than in LC1 and bio-based gasoline (BBG) is 40% higher.

All of these differences have implications for things like required fuel infrastructure and overall scenario costs. We consider these further below.

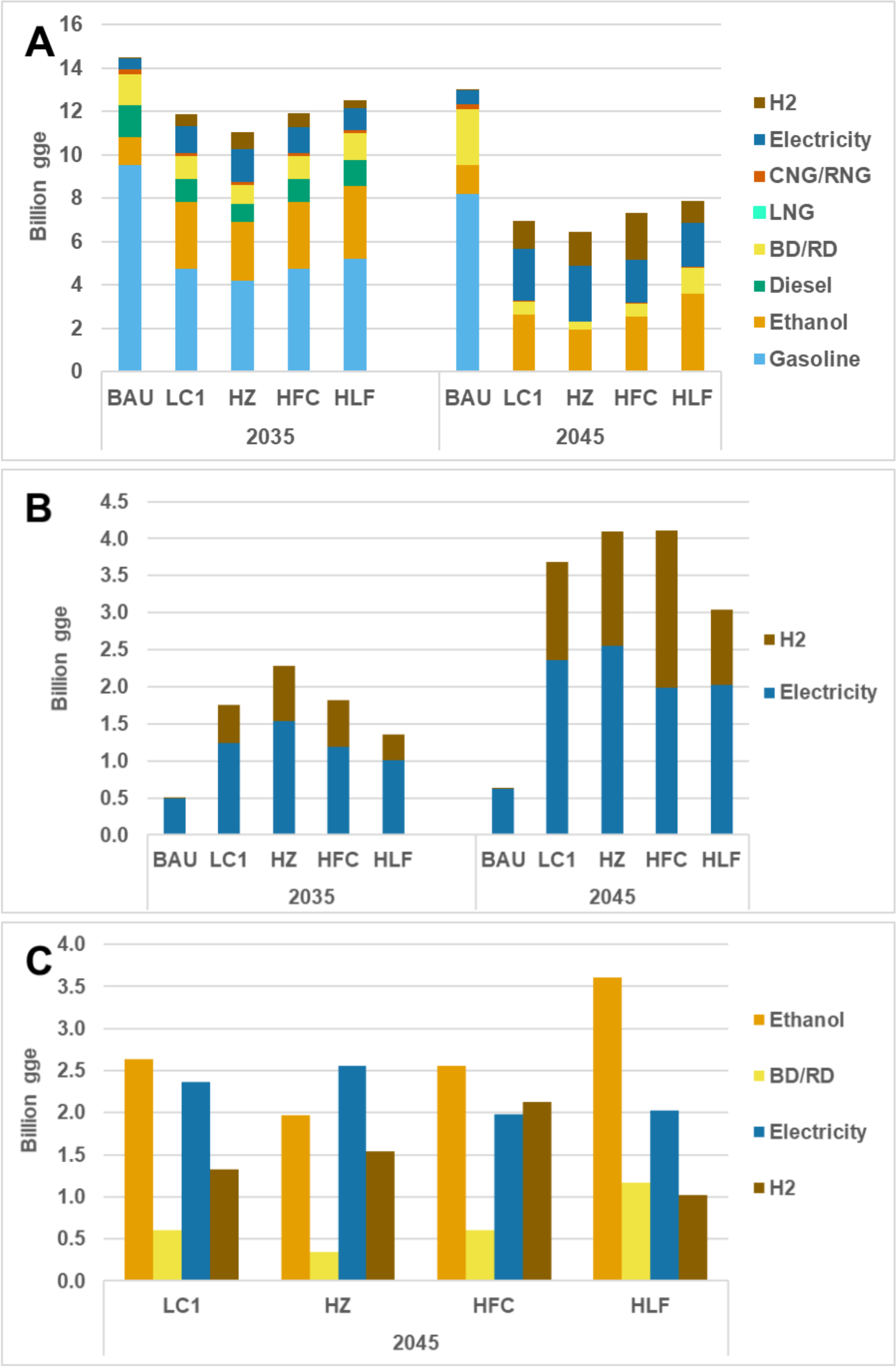


Figure 4.25. Fuel consumption by fuel type by year. (Panel B shows the same data as Panel A, focused on hydrogen and electricity; Panel C shows the same data as the right side of Panel A [year 2045], with adjacent rather than stacked bars for each scenario.) The increase in electricity, hydrogen, and biofuels is substantial from 2035 to 2045, with the biggest increase in electricity in the HZ case, biggest in hydrogen in the HFC case, and biggest for biofuels in the HLF case. (Note that the y-axes are on different scales; gge, gasoline gallon equivalent; H2, hydrogen)

The CO_2 emissions profiles (Figure 4.26) in all these scenarios are similar, both through their evolution and their levels in 2045, when they are all fairly close to zero. By 2045 the HZ case has slightly lower CO_2 emissions than LC1, given its greater use of near-zero CO_2 electricity and hydrogen. HLF has somewhat higher CO_2 emissions, given its relatively higher use of biofuels (even though they are advanced technology types). But the differences are small relative to the BAU.

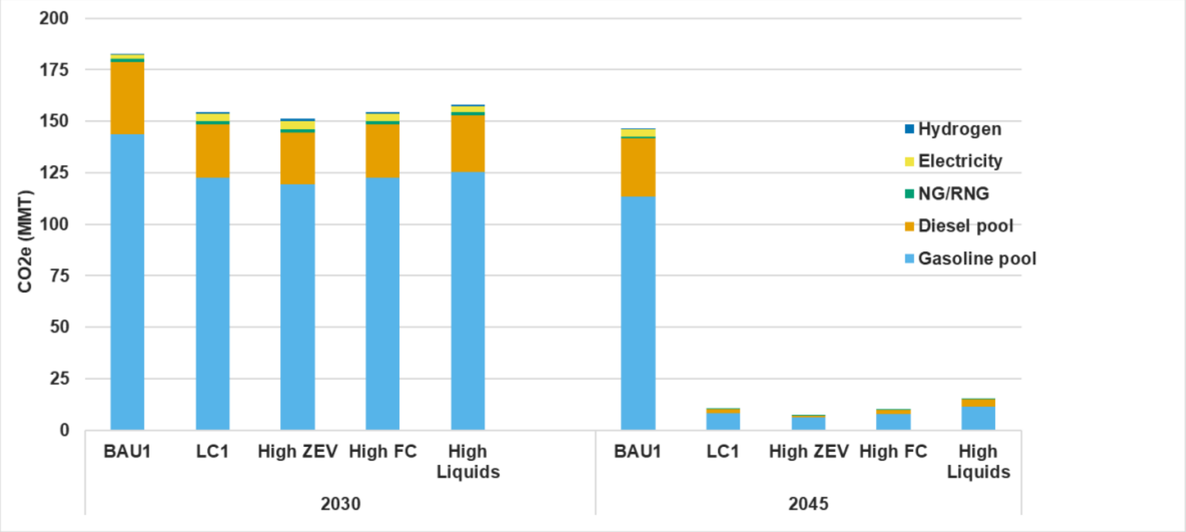


Figure 4.26. CO_2 emissions by fuel and scenario in 2030 and 2045

4.5.1 Comparison of Side case costs

As discussed above, the LC1 scenario saves on the order of $177 billion compared to the BAU between 2031 and 2045, although it does cost about $10 billion more between 2020 and 2030. Figure 4.27 shows each of the four cases in terms of their costs relative to the BAU. The left panel shows the incremental costs in 2020–2030; and the right panel shows these costs again along with the savings in 2031–2045. The right panel puts the 2020–2030 costs from the left panel into perspective, relative to the savings that follow.

Effectively, the different cases do not have strongly different costs compared to the BAU. During the 2020–2030 timeframe, the most expensive is the High ZEV (HZ) case, at about $12 billion including vehicles and fuels. (Note that fuel provides savings, shown below the x-axis.) This HZ case has a cost of about $2 billion more than the LC1 scenario. But the HZ case also provides the greatest savings from 2031 to 2045, around $191 billion vs. than the BAU; it saves $14 billion more than the LC1 scenario.

The High Fuel Cell (HFC) case does not cost appreciably more than LC1 in 2020–2030, in part because there are not that many more fuel cell vehicles until after 2030. During 2031-2045, it saves about $34 billion less than the LC1 saves (i.e., costs $34b more). The high liquid fuel (HLF) case costs the least until 2030, but again this is because the adoption of expensive advanced biofuels mostly occurs after 2030. Between 2031 and 2045 it saves about $18 billion less than the LC1 does, mainly due to the reliance on high-cost biofuels rather than relatively lower cost electricity (taking into account EV efficiency) use in LC1.

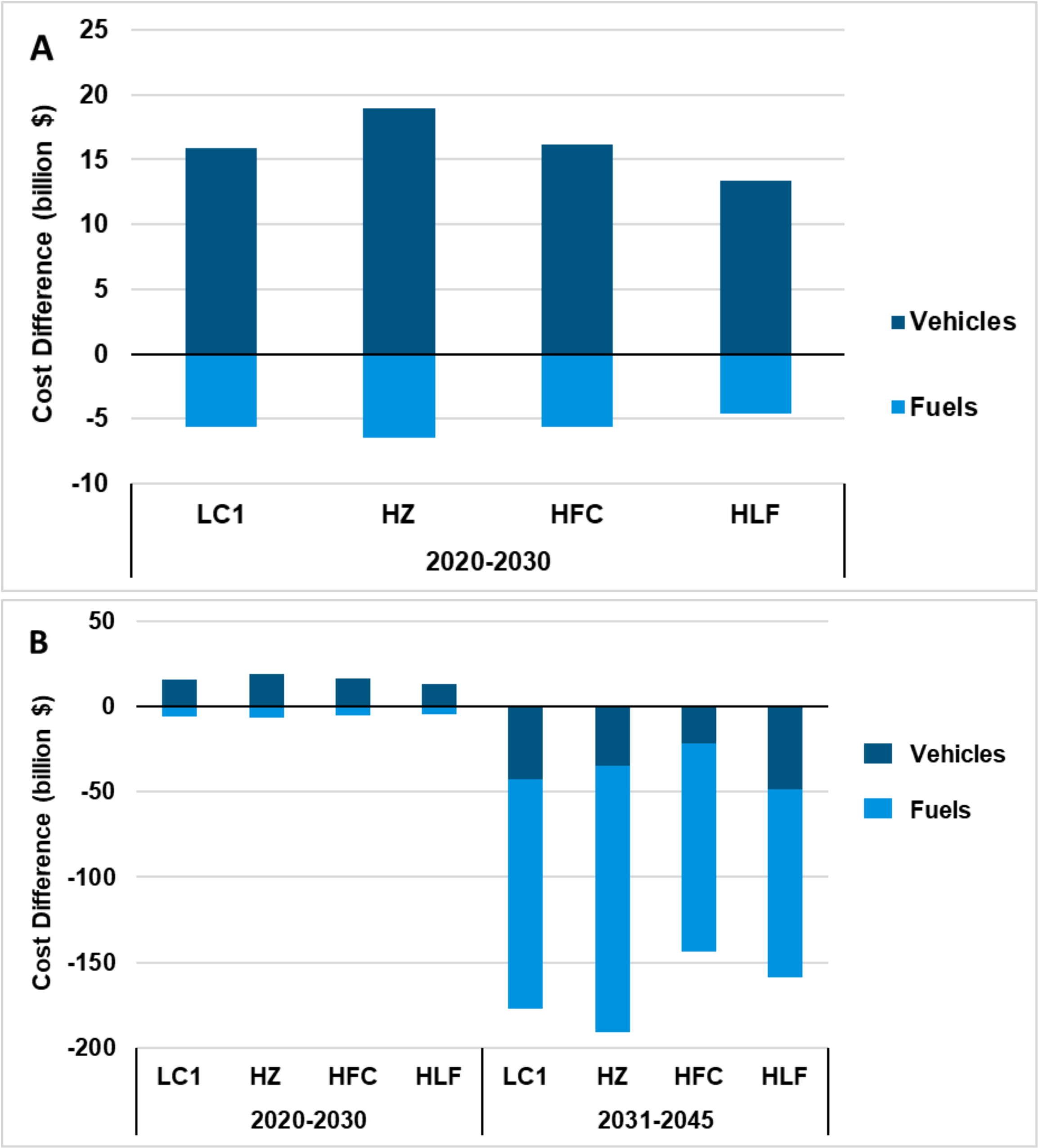


Figure 4.27. Cost differences between the LC1 and side case scenarios vs. (minus) the BAU scenario, in different time periods. (Note: Panel A is the same as the left side of panel B, but on a different y-axis scale.) The additional expenditures on vehicles and fuels from 2020 to 2030 is slightly higher in the High ZEV case than other cases, but it also provides the biggest savings after 2030. Savings in all cases after 2030 are far higher than costs before 2030.

4.6 Sensitivity Analysis

We performed a sensitivity analysis on the cost of gasoline, diesel, electricity, and hydrogen. The baseline, high, and low values are shown in Table 4.4. The gasoline and diesel represent a 25% increase and 25% reduction from the base value. The electricity costs include a five cent increase and decrease in the assumed average retail price across all charging. The hydrogen costs reflect our best estimate that long term, large scale hydrogen retail prices will range between 4 and 6 cents per kg.

Table 4.4. Sensitivity Case Input Values. Low, base, and high values for the cost of gasoline, diesel, hydrogen, and electricity used for the sensitivity analysis for the period 2020 –2045.

	Diesel Blend ($/gal)			Gasoline Blend ($/gal)			Electricity ($/kWh)			Hydrogen ($/kg)		
Year	Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High
2020		3.33			3.02		0.12	0.17	0.22	10.00	12.00	17.00
2025	2.80	3.73	4.66	2.38	3.17	3.96	0.12	0.17	0.22	7.00	8.50	12.00
2030	3.00	4.00	5.00	2.53	3.37	4.21	0.12	0.17	0.22	6.00	7.00	9.00
2035	3.07	4.09	5.11	2.61	3.47	4.34	0.12	0.17	0.22	5.00	6.25	7.00
2040	3.14	4.18	5.23	2.66	3.55	4.44	0.12	0.17	0.22	4.00	5.75	6.00
2045	3.13	4.17	5.21	2.71	3.61	4.51	0.12	0.17	0.22	4.00	5.40	6.00

The model was run with the high and low values for the LC1 and BAU scenarios and calculated the cost differences year by year through 2045. Table 4.5 shows the cost difference between the LC1 and the BAU scenarios for the time periods 2021–2030 and 2031–2045. The difference in 2020–2030 net costs of LC1, across the sensitivity cases, is a range from $7 to $14 billion more than the BAU. The net savings in LC1 from 2031–2045 vary from $105 to $250 billion. Thus the signs do not change but the net costs and savings over the time periods can vary by 100% or more depending on the fuel cost assumptions. Still, none of these results change the basic conclusion that after a decade of some net additional costs in LC1, there are likely to be very large savings after 2030.

Table 4.5. Sensitivity Case Costs. The expenditure cost difference in billions of dollars between the LC1 and the BAU scenarios for the sensitivity cases for the periods 2021–2030 and 2031–2045. The low and high oil cases include variation in both gasoline and diesel fuel.

Cost Sensitivity	2020–2030	2031–2045
Baseline LC1	10.3	-177
High oil	6.6	-250
Low oil	14.0	-105
High electricity	13.7	-123
Low electricity	8.9	-205
High Hydrogen	11.8	-171
Low Hydrogen	9.6	-194

The high and low oil cost cases, along with the original LC1 cost trajectories (showing combined vehicle and fuel costs), are shown in Figure 4.28, below. The figure shows that net expenditure costs decline over time in all the cases, but cross the "breakeven" point at slightly different time points, ranging from 2029 to 2031 in the high oil cost to the low oil cost scenarios respectively.

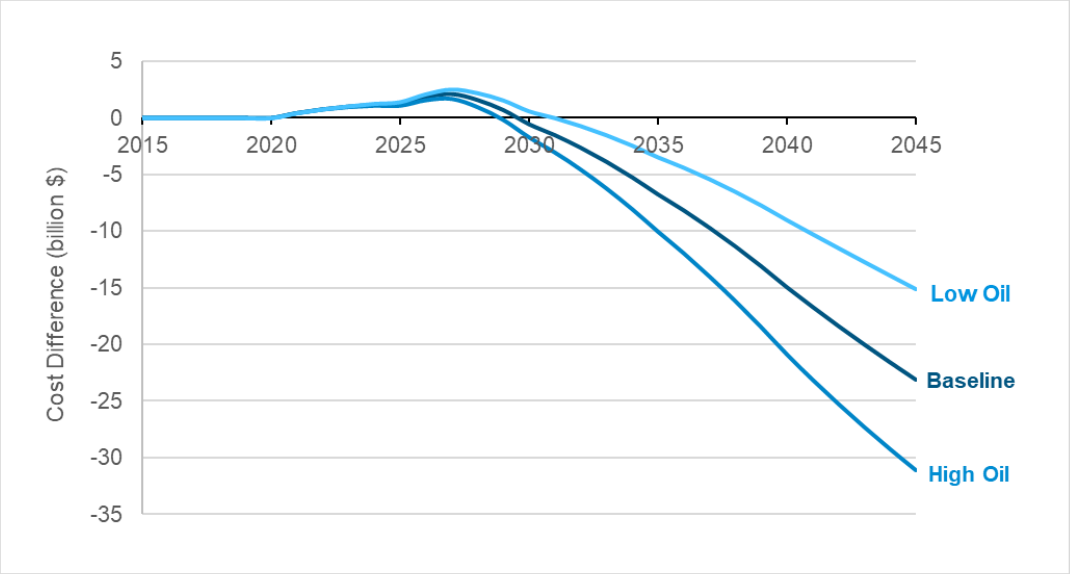


Figure 4.28. Expenditure Difference, LC1-BAU, for baseline, low, and high oil costs in the LC1 scenario. The three cases reach break-even with the BAU between 2029 and 2031, and all generate large savings after the breakeven year.

5 Policy Mechanisms

Good policy needs to balance many competing priorities. This is especially true for a system as complex as California's transportation system. Multiple transportation modes, technologies and use cases need to be guided by policy in order to reduce greenhouse gas emissions from the transportation sector. This includes lowering emissions from passenger vehicles and freight vehicles, improving access to and quality of public transportation while reducing emissions from that sector, improving access to active transportation, and building out infrastructure needed to support zero-emission electricity, fuels, and improved public rights of way.

The study was designed to address multiple principles in guiding policy analysis based on the necessary goals for getting to zero carbon emissions in transportation. Rapid decarbonization is needed to avoid the worse outcomes of climate change, and transportation, as the largest GHG emitting sector, requires the biggest transformation to achieve rapid decarbonization. The core motivation for this study is to explore pathways to a zero carbon transportation system for California by 2045. This goal is based on the best available climate science, which states we must achieve zero emissions by 2045 in order to limit climate change to a global average temperature increase of no more than 1.5 degrees Celsius [210]. As shown in Figure 5.1, transportation emissions must be reduced at a faster pace than what is expected under current policies in California, according to the most recent findings of the IPCC.

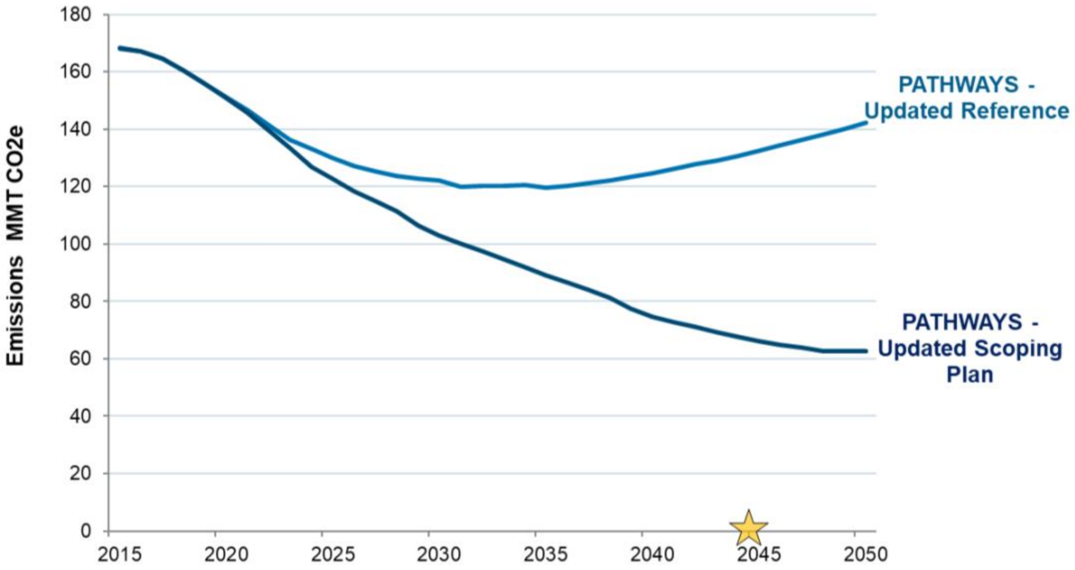


Figure 5.1. Tailpipe emissions from E3's Pathways model as used in the 2017 Scoping Plan. Transportation emissions will need to fall faster than currently expected under the integrated California policies, as reflected by the most recent scoping plan.

While the PATHWAYS analysis focused on the period to 2035, the model does go to 2050, so we used that trajectory as context for this analysis. The reference case was an estimate of the impact of existing pre-2017 policies. The Updated Scoping Plan scenario included new policies, including the key transportation policies discussed in the Business-as-Usual (BAU) (section 4.1) portion of this paper. The BAU used in this report differs from the scoping plan scenario in several ways, as discussed in Scenarios (section 4).

In addition to rapid decarbonization, this research was also required to address key priorities for the state. This includes:

- Equity and Justice: The study includes a detailed analysis of equity and justice in transportation, and each policy section includes policy options that can help ensure
- Health: The core findings of the public health benefits of transportation decarbonization are located in section 10, Assessment of Health Impacts.
- Environment: The core analysis of this study is around reducing GHG emissions.
- Resilience and Adaptation: While the focus of this study is on mitigation, future research will need to explore the key mechanisms for improving resilience in the transportation system simultaneously.
- High Quality Jobs: The workforce section includes a detailed analysis of possible effects by industry of the low-carbon scenario analyzed. It includes analysis of the nature of the affected sectors.
- Affordability and Access: The analysis includes estimates of the overall cost effects of the low carbon scenario, including some initially higher costs and extended savings from reduced fuel spending. Relevant sections also explore policies to protect lower-income transportation users. The analysis of transportation demand includes improved access as a key criterion.
- Minimize Impacts Beyond Our Borders: the analysis of fuels includes consideration of emissions across the full life cycle, including for imported fuels. The fuel supply chain is the primary point of concern for potential emissions leakage, and effective fuels policy can use a lifecycle approach to avoid incentivizing out-of-state fuels.

5.1 Milestones and Progress Tracking

In order to monitor the progress made from California policies, milestones in each sector should be achieved every five years, and updated accordingly. Transportation sector-wide goals are to achieve zero carbon emissions by 2045, which will require light-duty vehicles (LDVs), heavy-duty vehicles (HDVs), vehicle miles traveled (VMT) goals, as well as milestones for Fuel carbon intensity.

Table 5.1. Key milestones[15]

Subsector	2025	2030	2035	2040	2045
Sector-wide emissions (kt CO_2e)/reduction from 2015	212000 4%	166000 25%	105000 53%	53000 76%	Zero carbon
LDV	15%	50%	75%*	100% of new sales are ZEV	
HDV	10%	38%	63%	98%	100% of new Sales are ZEVs
VMT	4.8% per-capita VMT reduction from 2019 baseline	8.5% per-capita VMT reduction from 2019 baseline	9.9% per-capita VMT reduction from 2019	12.5% per-capita VMT reduction from 2019	15% per-capita VMT reduction from 2019
Fuels	Biomass based diesel <30 g/MJ average CI	500 mm gal/yr of <20 g/MJ drop-in gasoline 600 mm gal/yr of <25 g/MJ drop-in SAF	Petroleum fuels < ½ of total 500,000 tonnes/yr net-negative CCS	2 billion gal/yr of <12 g/MJ drop-in gasoline 0 petroleum diesel	2 billion gal/yr of <7 g/MJ drop-in gasoline 4 million tonnes/yr net-negative CCS
Workforce	Estimated annual full-time equivalent jobs in ZEV-related sectors exceed 100 thousand.			Projected annual expenditures on EV charging infrastructure reach nearly $9 billion.	Estimated annual full-time equivalent jobs in ZEV-related sectors exceed 500 thousand.

Due to uncertainty, it is likely that some milestones will be exceeded and others will not be met. Therefore, these milestones can be updated over time to reflect current needs and trends.

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[15] The analysis for these milestones were performed prior to the signing of EO N-79-20. They represent the minimum necessary progress to avoid the worst impacts of climate change, however, faster progress improve these chances. * This scenario element is not exactly aligned with the Governor's executive order (N-79-20) for 100% ZEV sales by 2035. This scenario was developed via independent research and so should not be viewed as incompatible with that goal. The accelerated ZEV side case analyzed does explore the emissions implications of a 100% sales by 2035 case.

5.2 Economy-wide policy

Historically, California has used a combination of economy-wide policy to reduce emissions from whole sectors. This has also helped the state target transportation emissions through several policies, including policies that help reduce emissions from transportation fuels.

5.2.1 Policies to support reducing carbon emissions from fuels

5.2.1.1 Cap-and-Trade in Transportation

California's cap-and-trade program is one of the few carbon pricing programs that covers on-road transportation fuels. Emissions from fuel suppliers who emit at least 25,000 metric tons of CO2 per year are covered by the cap, and the cap declines every year until 2050. Like other industries, suppliers must acquire permits to cover their carbon emissions [211].

Carbon pricing, such as carbon taxes or cap-and-trade programs, are widely regarded as an important and effective policy tool for reducing GHG emissions [212]. Many jurisdictions around the globe have adopted carbon pricing in some form. Most such systems gradually increase the carbon price over time; California's does so via a "floor" price for emissions allowances that increases faster than the rate of inflation. The gradual escalation of prices means that sectors with lower abatement cost opportunities decarbonize earlier than those with higher abatement costs. Emissions abatement through energy efficiency, industrial process efficiency and switching from fossil to renewable sources of electricity typically occur at lower carbon prices than most measures in the transportation system [213]. California's cap-and-trade program is likely to exhibit similar behavior; expected prices will have a much greater impact on non-transportation sectors [214]. Cap-and-trade price effects will contribute to reduced emissions from transportation, but not enough to achieve, or even approach carbon neutrality in 2045 without complimentary policies that provide a more immediate and impactful effect [215], [216]. Revenue from the cap-and-trade system may play a critical role in funding emission-reducing investments in transportation projects; these investments are considered in general fashion as contributing to the decarbonizaton efforts discussed in this report, but due to year-to-year variation in legislative funding priorities, we do not attempt to model the specific impacts of any given project.

Part of the funding from auctioned credits is then applied to several programs designed to increase low and zero carbon transportation through companion policies through the California Climate Investment program and the Greenhouse Gas Reduction Fund (GGRF). Programs receiving investments include the Clean Vehicle Rebate Program (CVRP), Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP), equity programs like financial assistance and Clean Cars for All, and freight projects like pilot programs for low carbon facilities. Companion policies to implement these programs include SB 375, SB 350, the Low Carbon Fuel Standard, SB 1383, Mobile Source Strategy, and the Sustainable Freight Action Plan [211].

5.2.2 Fuel taxes and transportation funding

Fuel taxes have historically been used to pay for transportation infrastructure including roads, highways, transit, and maintenance. Federal and state fuel taxes are implemented and utilized to fund California's transportation infrastructure. In 2019, SB1 took effect, and the California gasoline tax was increased to index to inflation. The federal gasoline tax is collected at the fuel terminal, before it is distributed to the point of sale, and returned to

California based on the point of sale [217]. As fuel efficiency increases, the relative revenue raised from gasoline taxes decreases per mile, and is eliminated if a vehicle is a ZEV and therefore does not use fuel. Because of this, California implemented a $100/year registration fee for electric vehicles to address the fact that they do not pay fuel taxes, but they do contribute to wear and tear on the road.

Research from UC Davis has shown that this method of implementing fees on electric vehicles is not a sustainable way to fund transportation infrastructure. In addition, it diminishes the incentives for people to purchase electric vehicles and does not provide any incentives for drivers to reduce their VMT. Instead, Jenn finds that a road user charge or similar program would be a more sustainable and equitable way to raise revenue for transportation infrastructure [16].

6 Light-duty Vehicle Electrification

6.1 Introduction

Achieving a zero-carbon transportation system in California by 2045 will inevitably require the retirement of light-duty internal combustion engine vehicles (ICEV) from the fleet. They will be replaced by zero-emission vehicles (ZEVs) including full battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). This section will explore the policies needed to perform this fleet transformation, focusing on one scenario described in the scenario section. Our focus will be on the policies necessary to overcome barriers and spur adoption of plug-in electric vehicles (PEVs) that replace ICEVs in the next 25 years (2020–2045). Our analysis demonstrates the effect of the drop in price of existing battery and electrification technologies between 2020 and 2030 on the cost of ZEV adoption; it does not consider development of potential new technologies after that period. Moreover, we explore the electrification process for privately owned light-duty vehicles assuming they are used in a similar fashion during the study time frame as they are presently; households retain the same number of vehicles and have the same annual vehicle miles traveled (VMT) over the study period.

In order to meet the state electrification goals the light-duty vehicle market has to shift from about 10% ZEV new car sales today to 50% in 2030 and close to 100% by 2040. Current research tools on this transition either focus on the preferences of today's potential buyers, the early adopters, or they perform aggregated scenario modeling of long-term fleet composition. Our review of the literature did not reveal tools or studies that estimate the ZEV adoption process beyond 50% market share. In addition to market penetration, impacts of adopting second and third vehicles in the household, potential demand for infrastructure at later stages of the fleet growth, and potential equity issues must also be considered.

To answer the questions about the need for infrastructure, market enhancing policies, and equity issues in order to meet the study's preset goal of full transition to almost 100% ZEV LDV fleet by 2040, we create a new three-step scenario modeling tool for this project. The first tool allocates the PEVs and FCEVs to different households based on their probability to adopt the first or an additional ZEV. This tool is based on preferences in early years and barriers for using plug-in vehicles in later years. The second model explores the demand for charging infrastructure at home, work, and public locations based on the predicted availability of home charging, commuting pattern, and vehicle type. Using the scenario results from the first two models we create a total cost of ownership (TCO) scenario to explore the cost or benefit of electrification for different segments of society by income and housing type. The new scenario tools were developed on a very short timeline and are limited in nature to demonstrate the policies needed but cannot forecast elasticities and funding requirements. We also do not include any sensitivity analysis which would help explore the relative impacts of different policies.

6.1.1 Current Policy

California has a set of policies designed to shift the light-duty vehicle market to clean transportation, thereby reducing local pollution, energy use, and greenhouse gas emissions.

On the supply side the ZEV mandate has been the most important policy driver of clean vehicle sales over the last decade. First implemented by California and since adopted by ten other states, the ZEV mandate uses a credit-trading structure. Automakers are required to sell an increasing percentage of ZEVs each year. If they cannot meet the requirement, they can purchase credits from other automakers that exceed the minimum percentage.

A second set of policies focusing on the demand side makes available a variety of monetary and nonmonetary incentives to ZEV buyers at the state and local levels. A recent study from UC Davis finds that the monetary incentives are getting more important over time as the market shifts from early adopters to more price-sensitive market segments.

The third set of policies is focused on the developing refueling infrastructure required for ZEVs, reducing barriers for installation, allocating funds, and regulating the use of both PEV chargers and hydrogen fueling stations for FCEVs.

6.1.2 Main Barriers

For the new car market to replace most of the ICEV sales with ZEV sales by 2040, it must accelerate this transition earlier and create a strong secondary market. Figure 6.1 shows that in the last four years only about one-third of Californian households purchased or leased a new car, with just 6% of the households purchasing one-third of the new cars.

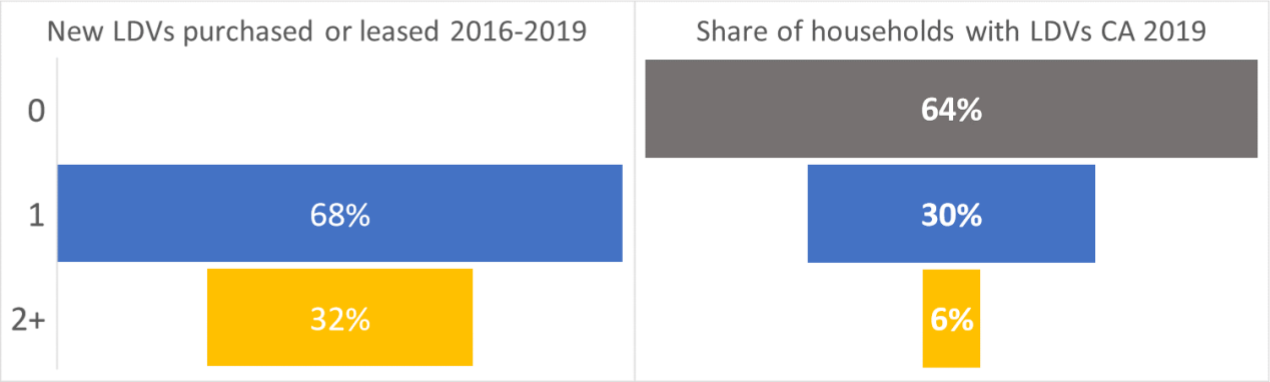

Figure 6.1. Who purchase new light-duty vehicles (LDVs) [218] (California Survey 2019)

Our main scenario suggests that more than 30 million ZEVs will be purchased by California households between 2020 and 2040 but only about 4–6 million households will be participating in the new vehicle market, purchasing new vehicles every two to four years and then passing those vehicles into the secondary market. We expect more people to buy their first ZEV used rather than new. In order to ensure the flow of new and used vehicles into the fleet we have to explore barriers slowing down the secondary market, including what may be reducing the attractiveness of used cars or reducing the residual value of used vehicles. Our modeling tools do not include the flow of vehicles between the new and used markets other than adding the cost of home charging only to the first PEV in the household and reducing the capital cost of ZEVs adopted by households who were more likely to purchase them used.

Awareness is an additional barrier we are not exploring in our scenario tool, which is based on current preferences for ZEVs and future benefits from electrifying. Recent work from UC Davis suggests that lack of awareness is a key factor in the low demand for ZEVs. A quick ramp-up of the market will have to overcome this barrier by both attractive pricing using incentives and new tools to create awareness. The same research also points to segments of the buyers who are committed to ICEVs and will not consider alternatives. This group may be a barrier in later years and will require additional considerations.

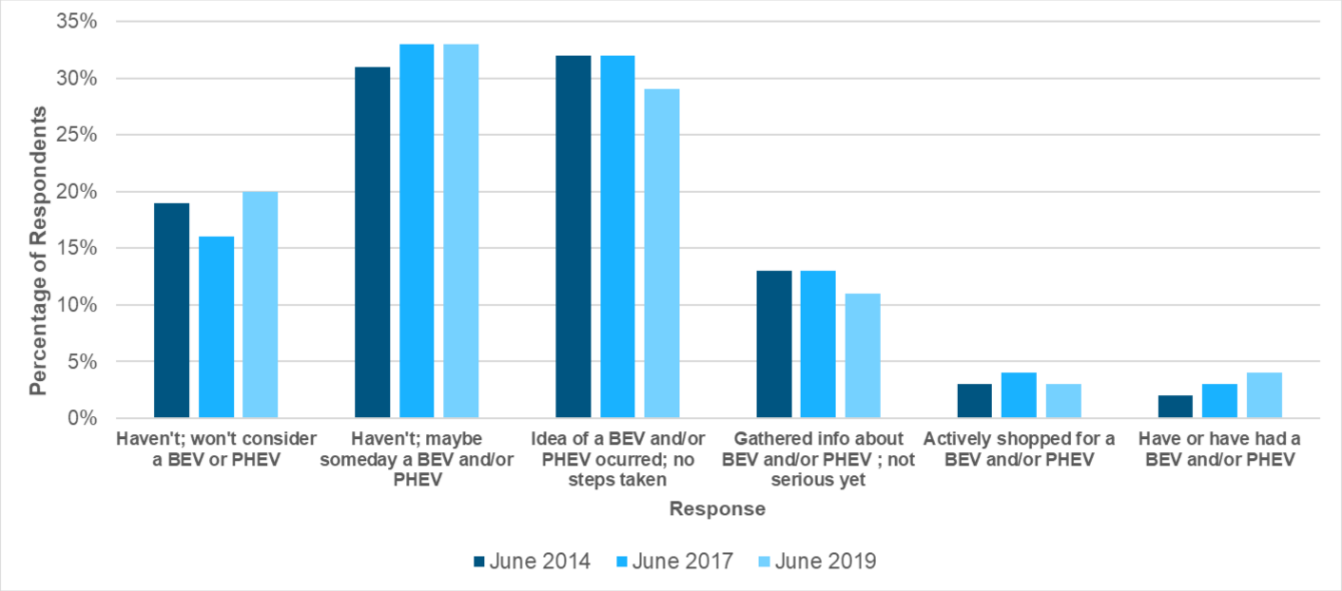

Figure 6.2. Consumer consideration of BEVs and PHEVs is unchanging. California; all car-buying households; percent; June 2014, June 2017, March 2019

6.2 Scenarios

6.2.1 Fleet Electrification Scenario Modeling

Electrification of the privately-owned light-duty vehicle fleet is central to the plan to create a carbon-neutral transportation sector in California. In order to expand electric vehicle ownership from less than 5% in 2020 to over 90% by 2045, the state will need to overcome three key obstacles: decreasing the costs of electric vehicles to enable more households to adopt their first electric vehicle, expanding the range of models available to allow more households to fully electrify their fleets, and finally providing a statewide charging and hydrogen fueling network to support the travel needs of ZEV-only households. This section presents a scenario for the spread of electric vehicle ownership across all California households based on the vehicle sales and fleet makeup scenario discussed in Section 4.

Fleet electrification is modeled at the household level, with adoption of the first household ZEV modeled separately from adoption of second and later vehicles. Wealthier households in single-family homes with larger fleets adopt their first ZEV sooner than households in other groups. Households that have adopted their first ZEV are eligible to add more ZEVs to their fleet at the rate of up to one per year until all their ICEVs have been replaced by ZEVs. This analysis divides households into five categories, grouped by annual income level (under $75,000, $75–$200,000, or above $200,000) and housing type (single-family or multi-unit). For the initial adoption step, these six categories are collapsed somewhat in order to roughly match the adoption categories identified in previous research: residents of multi-unit dwellings in the top two income categories are modeled together, and residents in the lowest income category are modeled together irrespective of housing type. Each category is further subdivided by number of household vehicles (1, 2, 3, 4, or 5+). Since the American Community Survey does not provide cross-tabulations of these variables, statewide totals for each household category were generated using synthetic population methods at the census tract level with data from the American Community Survey and the 2019 California Vehicle Survey. The resulting synthetic population was aggregated to statewide totals for all further steps of analysis. The statewide total number of households and vehicles in each group for each group are shown in Table 6.1, with the rough order in which each household type begins to electrify their household fleets shown in the Rank column.

Table 6.1. Total households and vehicles in the four groups used for fleet electrification modeling

Rank	Household Income	Home Type	Total Households in California	Total Vehicles
1	> $200k/yr.	Single family	1,135,000	2,999,000
2	$75-200k/yr.	Single family	3,506,000	8,365,000
3	> $75k/yr.	Multi-unit	1,257,000	2,084,000
4	< $75k/yr.	Any	7,056,000	13,116,000

This model separates the adoption of the first ZEV in the household from adoption of additional ZEVs in order to account for the significant barrier to adoption posed by adopting new technology and installing charging equipment. It is less risky for households with multiple vehicles to adopt a single electric vehicle than it is for a household with one or two vehicles. To account for this, households with fewer vehicles receive an adoption rate penalty that results in them adopting later than households in the same income and housing category but more vehicles. The estimated number of first-vehicle adoptions in each household category is estimated using a Bass diffusion of innovations model adapted from Lee et al. Once households have converted one vehicle to a ZEV, they become eligible to convert additional vehicles to ZEVs at a rate of up to one per year. Additional vehicles after the first are electrified at equal rates across all households, with the adoption rate varying from year to year based on the number of ZEVs added to the market, after first adoptions and replacements are accounted for.

This ZEV adoption model rests on of the following key assumptions:

a. Electrifying the first vehicle in a household is the key step in adoption since it requires an investment in charging infrastructure and for household members to adapt their behavior to a new technology. Once households adopt a new vehicle technology, they will gradually replace the rest of their fleet.
b. Income and housing type are the primary controls on electric vehicle adoption. Wealthier households that can afford to purchase new vehicles and install charging infrastructure at home will adopt ZEVs sooner than households that cannot afford to invest or live in a house where charging infrastructure cannot be installed. Multi-vehicle households will convert their first vehicle sooner than single-vehicle households, but will electrify their household fleet one vehicle at a time.
c. Relative proportions of household types and vehicle ownership patterns will not change over the study period. If vehicle ownership decreases, that will be most significant among the households with the largest vehicle fleets, who will, for example, downsize from five to four vehicles. This sort of change would not substantially impact these results.
d. Electrification is permanent: once a household has replaced an ICEV with a ZEV, they will never replace that ZEV with an ICEV.
e. Every new vehicle sold replaces an existing vehicle, and there is little to no friction in the market for used ZEVs. A small fraction of households account for most new vehicle sales, and most other households primarily purchase vehicles used. As a result, new ZEV sales and the corresponding replacement of an ICEV will occur in different households. By assuming that the market for used ZEVs works smoothly, we can attribute all new ZEVs sold to one of three events: electrifying the first household vehicle (and thus requiring an infrastructure investment, where possible), replacing additional ICEVs in households that already have at least one ZEV, and replacing retired ZEVs.

6.2.1.1 Fleet Electrification Modeling Results

This scenario breaks electric vehicle adoption down by household type and vehicle-by-vehicle. Adoption begins with the first vehicles of high-income households in single-family homes, and eventually spreads to lower income households and residents of multi-unit dwellings while early adopters simultaneously convert to full ZEV fleets. The household categories used for this analysis are, in order of their rate of electrification: 1) “inc gt 200k, single family” households with a single family home, with an income (“inc”) of $200,000 or more (greater than “gt”) per year; 2) **“**inc 75-200k single family” households with a single family home, earning between $75,000 and $200,000 per year; 3) **“**inc gt 75k, apartment” households in multi-unit dwellings earning at least $75,000 per year; and 4) “inc lt 75k” households in any housing type earning less than (“lt”) $75,000 per year.

This analysis uses sales and fleet makeups aggregated across all types of ZEVs, but the results used in the scenarios for charger demand and TCO disaggregate results by vehicle type. Figure 6.3 shows the transition of vehicle ownership separated by home type. BEVs account for most of the electrification, and PHEVs and FCEVs support the electrification of households that cannot charge vehicles at home or require more range than affordable BEVs can provide. Even by 2045, about a quarter of the light-duty vehicle fleet will still require liquid fuel at least occasionally.

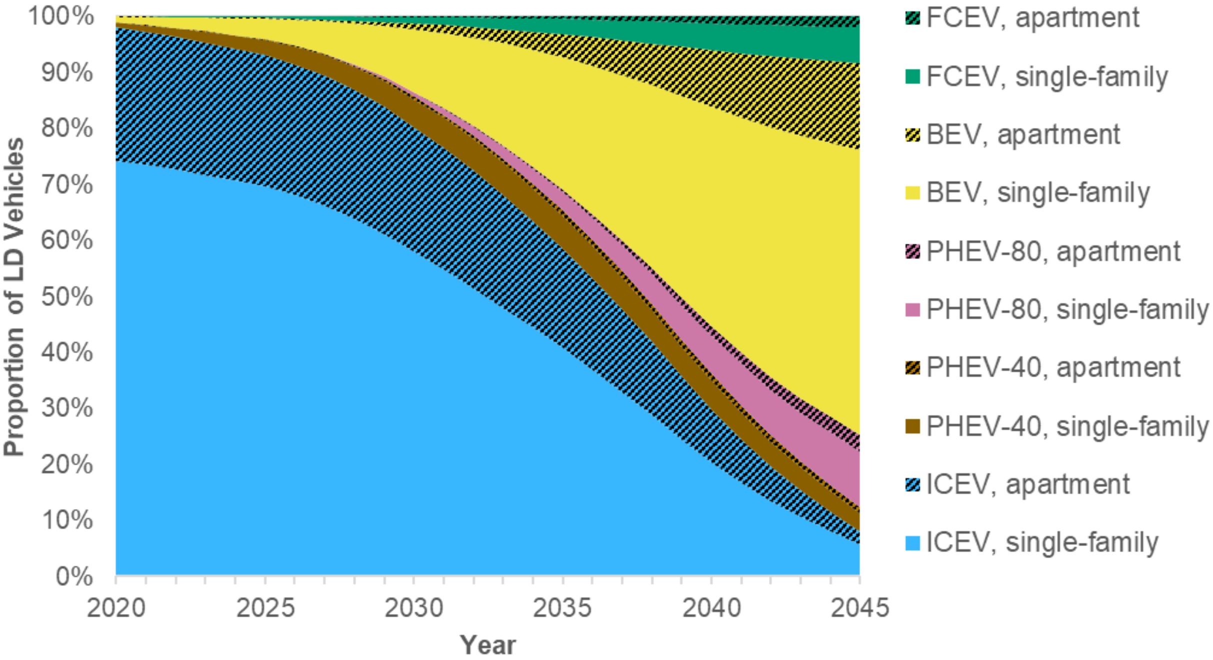

Figure 6.3. Adoption of first vehicle by household group and fleet size. (LD, light-duty)

PEV adoption requires charging infrastructure and an affordable supply of vehicles; as a result, adoption will be most rapid among high-income households in single-family homes and slowest among people who cannot afford either new vehicles or home chargers. Figure 6.4 and Figure 6.5 show the rate of adoption by household type and household fleet size. ZEV adoption through 2025 will remain heavily concentrated among high-income households with single-family homes and middle-income households in single-family homes with at least three household vehicles. Growth from 2025–2030 will expand into middle- and high-income households in apartments and become nearly universal among middle- and high-income residents of single-family homes. From 2030 to 2035, adoption will begin expanding into all household categories, and at least 20% of all groups except low-income households will have at least one ZEV by this point. By 2040, at least 60% of households in all groups except low-income households with only one vehicle will own at least one ZEV. The challenges of being fully ZEV-dependent mean that single-vehicle households are expected to lag in adoption by five years behind two-vehicle households and by as much as 10 years behind households with larger fleets.

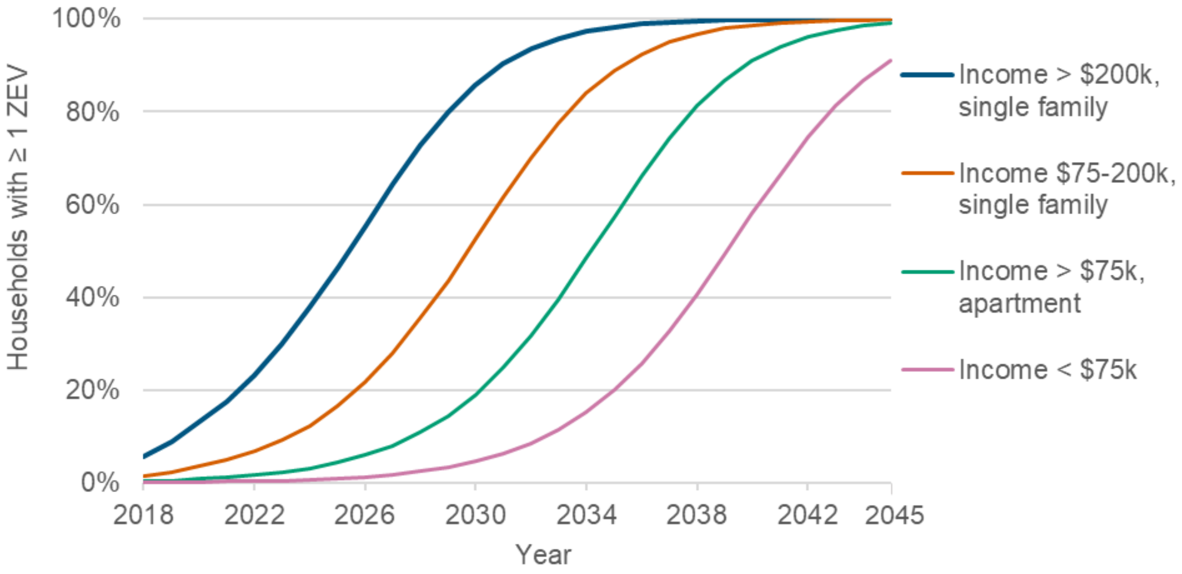

Figure 6.4. Adoption of first ZEV by household type

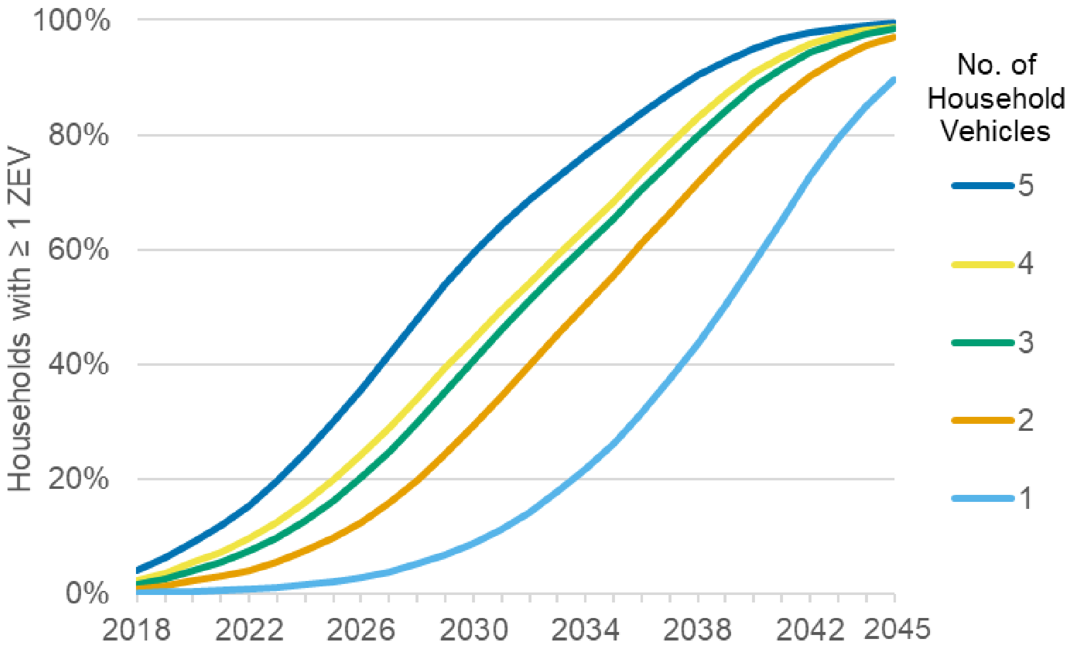

Figure 6.5. Adoption of first ZEV by number of household vehicles

As ZEV sales increase over the study period, ZEV adoption will gradually move from the first vehicle in the household to additional vehicles Figure 6.6. From 2020–2025, ZEV sales are a relatively small fraction of all light-duty vehicle sales, and most new ZEVs will contribute to the electrification of the first vehicle in the household. Over the next five years, as ZEV sales rapidly increase, a growing share of new ZEVs will go to the electrification of the second and third vehicles in the households. After 2030, most new vehicle sales will be ZEVs, and about an equal mix will be used to electrify the first vehicle in the household and to electrify additional vehicles. By the late 2030s, most households in California will have at least one ZEV and most sales will go to electrifying additional vehicles or replacing retired ZEVs.

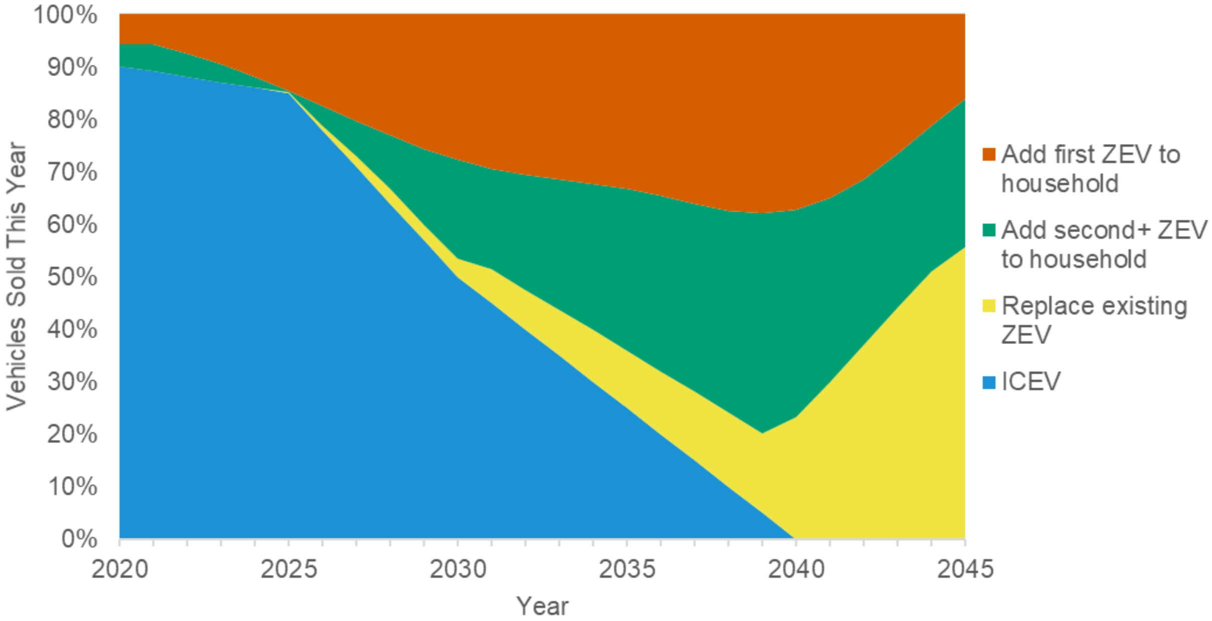

Figure 6.6. Allocation of new vehicles by what they replace

In the first ten years of the study (2020–2030), almost all ZEVs will be owned by households with single-family homes in the medium- or high-income categories Figure 6.7. These households will generally be able to install chargers at home, but some may choose to charge elsewhere if charging is cheaper and widely available at work or other locations. After 2035, much of the growth in ZEV ownership will be among the large category of households in the lower income category. These households are much less likely than wealthier households to be able install chargers at home, which suggests that shared charging infrastructure may be especially important to supporting the growth of ZEV ownership in this period. Middle- and high-income residents of multi-unit dwellings are also likely to require shared charging infrastructure, but they own a much smaller number of vehicles than the other three categories.

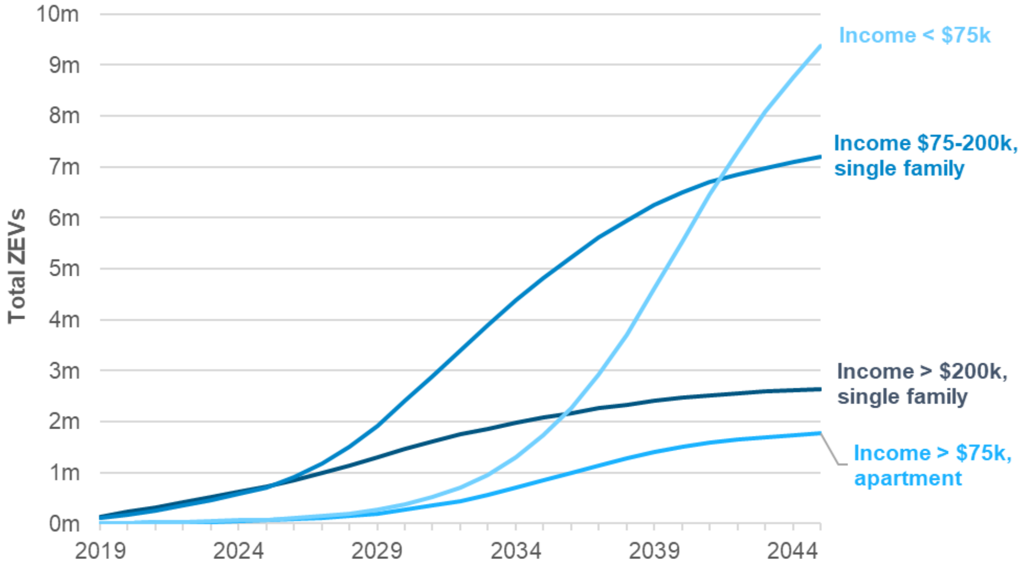

Figure 6.7. Total ZEV ownership by household category

Once fleet electrification accelerates after 2025, electrification of first vehicles is expected to be three to four years ahead of second vehicles, about five years ahead of third vehicles, and six to seven years ahead of fourth and fifth vehicles for households with large fleets. These adoption patterns have a substantial impact on infrastructure needs: demand for home charging begins with the first PEV owned by a household, but there may be limited demand for an extensive network of fast public chargers as long as most households still own an ICEV to use for long-distance travel.

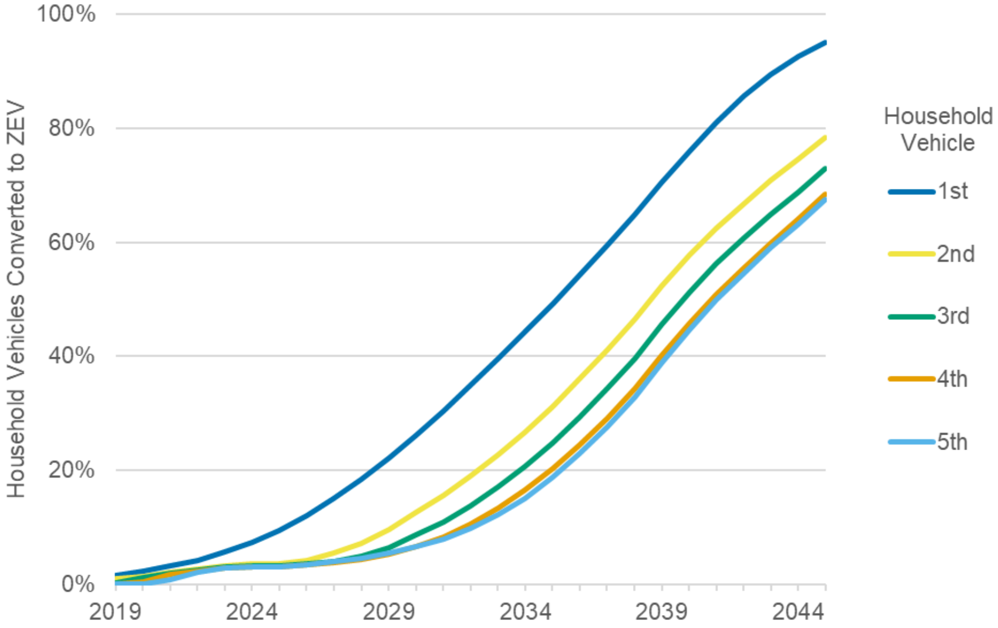

Figure 6.8. Electrification progress by first, second, etc. vehicle in the household

This model did not incorporate a few important factors that could significantly affect the adoption of PEVs into California households. Specifically, we acknowledge that there are many aspects of the secondary market that could impact both the new and used markets in California. One potential scenario, a strong new PEV market in California and simultaneously comparatively weaker markets in neighboring states, could lead to a larger than typical flow of used vehicles to the secondary markets outside of California. There are also unknown factors at the federal level, such as changing corporate average fuel economy (CAFE) standards, national ZEV regulations, or extending ZEV purchase incentives that would all affect the market growth nationally and in California, and are not included in our current modeling efforts.

6.2.2 Charging Demand Scenario Modeling

Charging demand was modeled at the level of individual vehicles and summed to produce an estimate for total statewide demand. The modeling process entails first estimating the annual mileage of each vehicle, then allocating those miles to home, work, and public charging, and finally converting the miles charged into an estimate for chargers needed. Vehicle miles, access to charging, and final charger allocation all depend on household income, home type, whether the vehicle is used for a commute, vehicle type, and the number of PEVs in the household. The main charging infrastructure scenario is built from two base charging scenarios: home-/night-priority charging, which maximizes charging at home while using commute and public charging to fill in the gaps; and work-/day-priority charging, which maximizes charging at work among commuters.

The estimated charging demand of each vehicle is built from three components: the miles it drives each year, whether it can charge at home, and whether it is used for a commute. Annual miles traveled per vehicle and the probability a given vehicle is used for commuting are derived from the 2019 California Vehicle Survey, with estimates produced for each household type, income, and household fleet size. Access to charging at home is a function of household type and income; it is higher for residents of single-family homes than for residents of multi-unit dwellings and is higher for households with higher income. Additionally, higher-income households are substantially more likely to install Level 2 chargers, whereas lower-income households are more likely to rely on level 1 charging. Nightly Level 2 charging can support almost any regular driving pattern, but Level 2 chargers are expensive to install, and many households may not have room to install multiple chargers. To account for charger congestion, vehicles in multi-PEV households are assigned less home charging than vehicles in otherwise similar households with fewer PEVs.

Each vehicle's charging is divided among home, work, and public charging with one scenario generated for non-commuters and two for commuters: home-priority and work-priority charging. For all vehicles, home charging is limited by access to charging and congestion. Work charging cannot exceed 6,300 miles per year (equivalent to charging at moderate speed for most of the day on most workdays). Public charging has a lower limit of 10% for all vehicles and no upper limit; in all scenarios, charging needs that cannot be met at home or work are assigned to public charging. Home-priority commute vehicles are only assigned work charging if they cannot meet their needs at home. Under home-priority charging, a commute vehicle that can cover at least 90% of its travel with home charging will charge 10% at public locations and not charge at work, and a commute vehicle that cannot charge at home will get the maximum charging at work and the rest at public locations, generally producing a fairly even split. Work-priority commute vehicles always charge the maximum at work, use home charging for as much as they can, and use public charging if home charging is unavailable. Non-commuters always charge as much as they can at home, up to 90% of their total miles, and make up the remainder on public chargers. To account for non-electric miles, these numbers are reduced by 30% for PHEVs with 40 miles of electric range and by 15% for PHEVs with 80 miles of electric range.

In order to estimate the total demand for chargers, work and public charging are converted to charging events, and total charging events are converted into an estimate for charger demand. Home charger demand is not linked to charging events, since a charger is assigned to every household that has a PEV and can install a charger. Miles per charging event varies by charging location and scenario. Under the home-priority charging scenario, charging events at work provide slightly more miles than public charging events because vehicles stay at commute destinations much longer than they stay at public charging locations, but workplace chargers are generally lower-speed than public chargers. The work-priority charging scenario assumes that vehicles will be used either for vehicle-to-grid (V2G) storage or charged in a way that minimizes the upstream emissions from electricity generation; both of these options decrease average charging speed, so work-priority charging events provide substantially fewer miles.

Events are converted to total demand for chargers based on the number of events a charger can supply in a year. Home-priority charging assumes that vehicles that charge at work will have to share chargers, and each charger will provide two charging events per day on workdays. Work-priority charging assumes that each vehicle will remain plugged in for the whole day in order to optimize electricity usage, so demand for chargers is essentially equal to the number of vehicles assigned to the work-priority scenario. Public charging is split into Level 2 and DC Fast at this point in the model, with 20% of BEV public charging being assigned to DC Fast. PHEVs are assumed to make minimal usage of DC Fast charging because their hybrid engine provides for long-range travel and faster refueling than DC Fast charging can provide. Because charging events are generally shorter and are not limited to workdays, public Level 2 and DC Fast chargers can provide substantially more charging events than workplace chargers. Because long-distance travel is highly concentrated in specific periods of the year, demand for DC Fast charging is inflated to ensure that there are sufficient chargers to meet demand during peak times.

Finally, the two charging scenarios are blended to produce a transition scenario. The blended scenario is identical to the home-/night-priority scenario in 2020 and begins to transition towards the work-/day-priority scenario starting in 2025. The final scenario for 2045 assumes that work-/day-priority charging will affect 80% of PEVs used for commuting. This transition helps drive a substantial increase in the demand for chargers at commute destinations in the final few years of the study.

The charging demand scenario rests on of the following key assumptions:

a. The choice of what type of ZEV to own is independent of household type, income, commute usage, and household fleet.
b. PEVs will have about the same behavior/will be used for commuting at about the same rate as ICEVs throughout the study period.
c. Income and housing type are the major controls on the ability to charge. More single-family homes than multi-unit dwellings will have any access to charging, but charger congestion will be more severe in single-family homes.

d. People will primarily charge where it’s cheapest. Charging at home is generally the cheapest option when available, except under the work-priority charging scenario. Public charging is assumed to be the most expensive in all scenarios.
e. All PEV drivers will use public charging occasionally, but only drivers without access to charging either at home or work will use public charging for a substantial amount of their miles. DCFC will make up a portion of public charging for BEV drivers, but will not be used by plug-in hybrids.

Over the study period, the number of chargers needed to supply the PEV fleet will gradually increase across all charger types. Home Level 2 chargers will be the most common type of charger until 2045, when the switch to work-/day-priority charging would require even more chargers at commute destinations Figure 6-9. Since this model assumes that every household that can install a charger at home installs one, but households do not install multiple chargers, the ceiling for household Level 2 charging stock is around 6 million. Some multi-PEV households today install multiple chargers, and this practice might become more common if chargers become considerably less costly. Multi-unit dwellings are another major source of uncertainty for this analysis, since they may have similar options to workplaces for managing charger demand among large groups of vehicles.

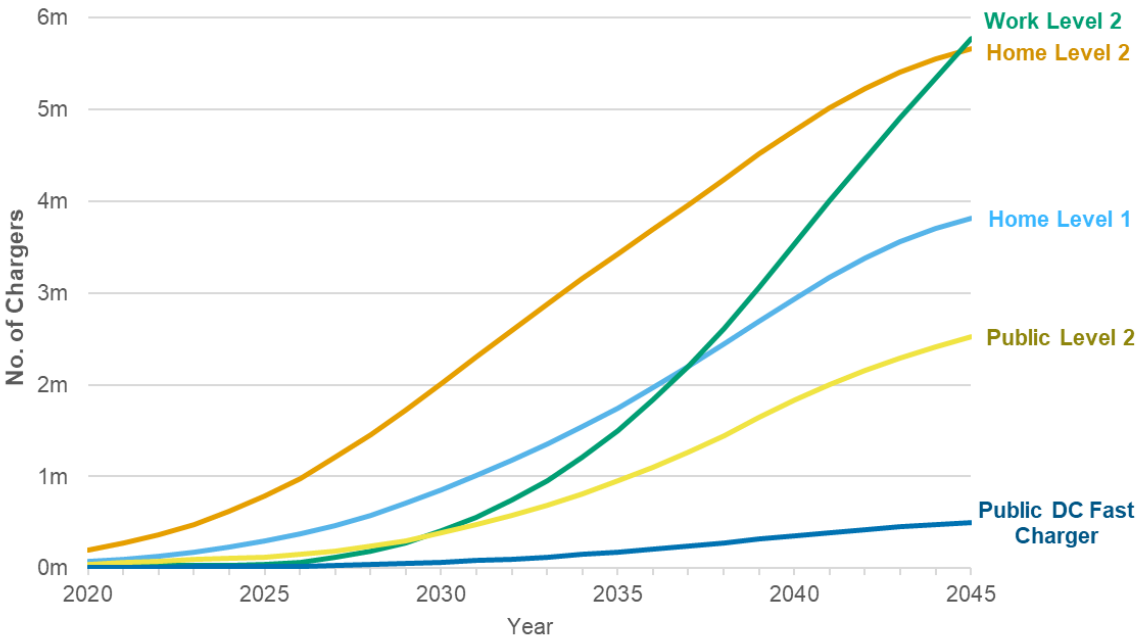

Figure 6.9. Charger stock

Annual demand for new chargers peaks in 2031 at almost 300,000 chargers per year for home Level 2 and around 2040 for other charger types. An aggressive switch to emphasize daytime charging at workplaces late in the study period would require a substantial increase in charger installation, with demand peaking at over 450,000 chargers per year in the early 2040s. Late adopters of PEVs will be much less likely to be able to charge at home and will require significant investment in public charging infrastructure, but the demand for new public chargers will not surpass demand for home or workplace chargers until the end of the study period. DC Fast Charging locations make up a small share of all chargers, but they will become increasingly essential for supporting long-distance travel as more households become PEV-only towards the end of the study period. Because of the extremely high installation costs for DCFC infrastructure, the peak demand of almost 40,000 new chargers per year will represent a substantial investment.

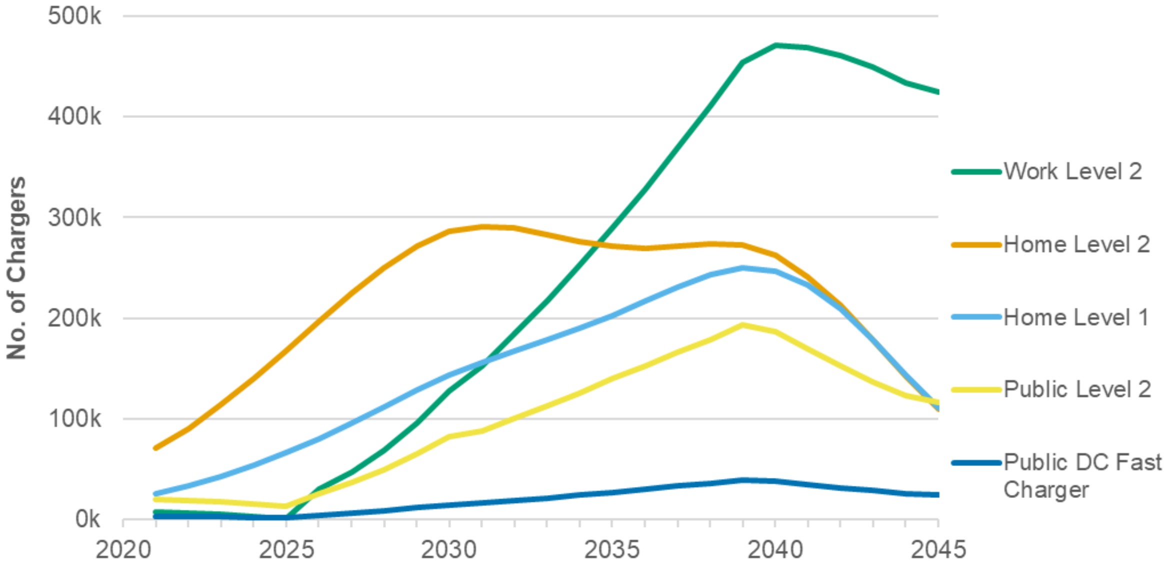

Figure 6.10. Demand for new chargers through 2045

The major change in charging behavior over the course of the study will be the decrease in the importance of home charging from almost 80% of all charging in the first five years of the study to 56% by 2045 Figure 6.11. The difference will be made up by substantial increases in both work and public charging, which will account for 17% and 28%, respectively, of all charging in 2045.

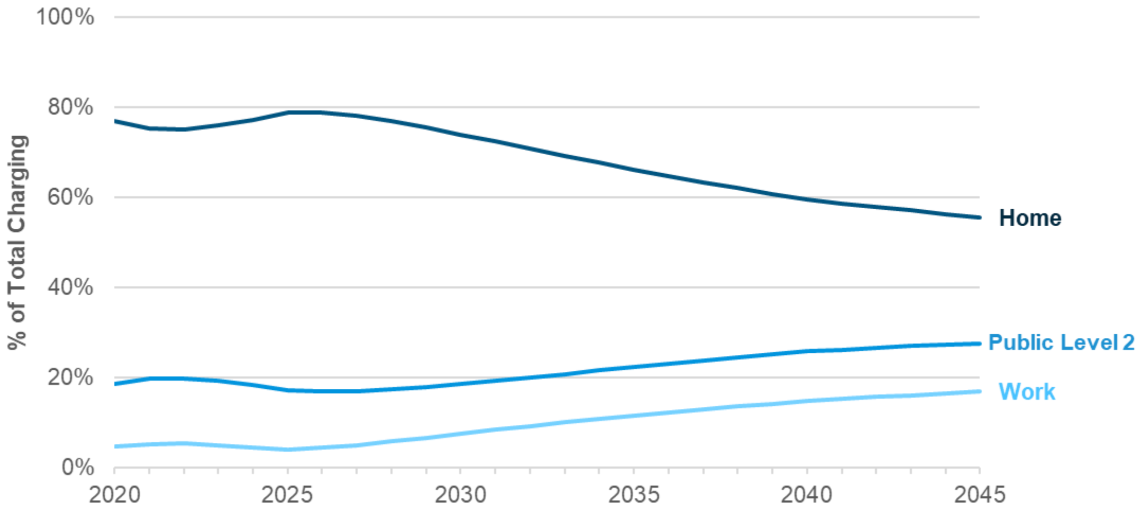

Figure 6.11. Proportion of charging by location – home, work, or public level 2

6.2.3 Total Cost of Ownership Scenario Modeling

A major concern associated with the goal of achieving a zero-carbon transportation system by 2045 is the cost of transitioning from an ICEV-dominated fleet to one where almost 100% of the vehicles are ZEVs. Comparative analysis of the TCO of ZEVs and ICEVs is one way to analyze the cost of electrification. This section will evaluate the cost of the specific fleet transition scenario described in the previous section. We compare the monetary cost of transitioning to ZEVs to the cost of continuing with a comparable ICEV fleet for the years 2020 to 2045 for the categories of households defined based on annual household income (less than $75,000, $75,000–$200,000, and greater than $200,000) and dwelling type (single-family/apartment and others).

Generally, TCO analyses are cross-sectional, focusing on a few ZEV types and comparing their cost of ownership to specific gasoline vehicles often chosen based on their popularity in the corresponding vehicle segment. Though some of these past studies have addressed the potential heterogeneity in the cost of electrification for different segments of the population it is mostly in terms of their geographic location and their VMT. Here, in addition to variation in VMT, we address the heterogeneity in the cost of electrification that may arise due to socio-demographic characteristics like dwelling type and income. Household income and dwelling type can influence a household's vehicle fleet size and composition, access to charging infrastructure at home, work, and public/non-work locations, and total VMT.

TCO of a vehicle has three main components: capital cost, operating cost, and resale value of the vehicle.[16] As mentioned earlier, here we first demonstrate how the fall in vehicle price of existing ZEV technologies (BEVs, PHEVs, and FCEVs) from 2020 to 2030 impacts the capital cost and consequently the total cost associated with the electrification process. The price of ZEVs falls in 2020 and 2030 as the cost of the battery technology and other direct costs associated with vehicle manufacturing falls. On the other hand, the price of gasoline vehicles increases under the assumption that the CAFE standards tighten over the years forcing manufacturers to make fuel-efficient vehicles. Second, we demonstrate how changes in fuel price and accessibility to charging infrastructure can impact the operating cost of gasoline and ZEVs over the study period. Accounting for the transition to renewable energy sources in California at the electricity grid-level and the potential of economical daytime charging, a higher proportion of charging events and thereby VMT is assumed to be electrified with workplace charging in the later years. As mentioned earlier, annual VMT varies across the six household categories but they remain constant over the study period. In other words, we assume that households have the same number of vehicles and drive them in a similar fashion as the present. This is a strong assumption about travel and vehicle choice behavior, but it was required to keep the analysis simple and understandable. Finally, annualized TCO of twelve ZEV options and the cost of adoption at the fleet level is evaluated for the light-duty vehicle electrification scenario demonstrated here. Assuming a vehicle lifetime of 14 years, the resale value of the vehicle is assumed to be its scrappage value, i.e., 5% of the purchase price of the new vehicle.

The twelve ZEV options considered are: short-, mid-, and long-range BEV passenger cars (PC); short-, mid-, and long-range BEV passenger trucks (PT); PHEV-40 PC and PT; PHEV-80 PC and PT; and fuel cell PC and PT. The details of the assumptions and the method for TCO calculation and fleet adoption cost is given in Appendix

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[16] Here, we only consider the private total cost of ownership. The social cost of ownership of a vehicle that accounts for the environmental cost of vehicle ownership is not a part of this analysis.

14.1.4 (iii)Total Cost of Ownership and Cost of Adoption Calculations - Model. For a comparative analysis of the cost of electrification to the cost of persisting with an ICEV dominant fleet, we consider three categories of gasoline vehicles: gasoline PC (non-luxury), gasoline PT (non-luxury), and gasoline passenger. Instead of selecting a single gasoline car or passenger truck as the representative vehicle for the comparison of vehicle purchase price, we consider the average MSRP of the five highest-selling gasoline vehicle models in the midsize car and SUV group for the non-luxury categories and the “Near-Luxury” groups for the luxury categories.

In Tool 1 described earlier, households in each year of the study period are allocated a type of ZEV based on their income, dwelling type, existing fleet size, and number of ZEVs already adopted. There is no differentiation between passenger cars, trucks, or other vehicle body types. Since the cost of passenger trucks is considerably higher than the cost of cars, for the TCO analysis we differentiate between these vehicle segments. Households are allotted a passenger car (PC) or passenger truck (PT) based on the system described in Table 6.2. Moreover, low-income households are less likely to buy new ZEVs, especially in the initial years when the price is high. Thereby, we rescale the new ZEV sales estimates derived in Tool 1 using California Vehicle Survey data to reflect the vehicle purchase behavior of the six categories of households analyzed here. Due to the rescaling, high- and middle-income households tend to buy a higher share of new vehicles in the fleet. Though high-income apartment dwellers are a small share of households, these households tend to buy a higher proportion of new vehicles than any of the other categories.

Table 6.2. ZEV allotment rule for TCO comparison

Household Type (Fleet Size + Number of PEVs/ZEVs)	ZEV Allotted	Gasoline Vehicle
1 vehicle + 0 PEV	FCEV- PT	Gasoline PT
2/3/4/5 vehicles + 0 PEV	FCEV- PC	Gasoline PC
1 vehicle + 1st ZEV	ZEV-PT (LR BEV- PT)	Gasoline PT; Luxury Gasoline PT for BEV LR PT, PHEV-80 PT
2/3/4/5 vehicles + 1st ZEV	ZEV-PC (MR BEV- PC)	Gasoline PC
2/3/4/5 vehicles + 2nd ZEV	ZEV-PT (LR BEV-PT)	Gasoline PT; Luxury Gasoline PT for BEV LR PT, PHEV-80 PT
3/4/5 vehicles + 3rd ZEV	ZEV-PC (MR BEV- PC)	Gasoline PC
4/5 vehicles + 4th ZEV	ZEV-PT (SR BEV-PT)	Gasoline PT; Luxury Gasoline PT for PHEV-80 PT
5 vehicles +5th ZEV	ZEV-PC (SR BEV-PC)	Gasoline PC

Given the vehicle allocation scenario built in Tool 1, in the year 2020, 54% of the PEV-owning households had only one PEV in their fleet and were mainly single-family home dwellers in the high- and middle-income category. As observed in Figure 6.12, a similar pattern is observed in 2025 with a higher percentage of high- and middle-income single-family households becoming a single PEV household compared to 2020. From 2030 onwards, the share of households with multiple PEVs starts to grow and more low-income households start entering the market. According to the ZEV allocation rule, as a result, a higher number of PCs and short- and mid-range PTs are allotted to the PEV-owning households than the earlier years.

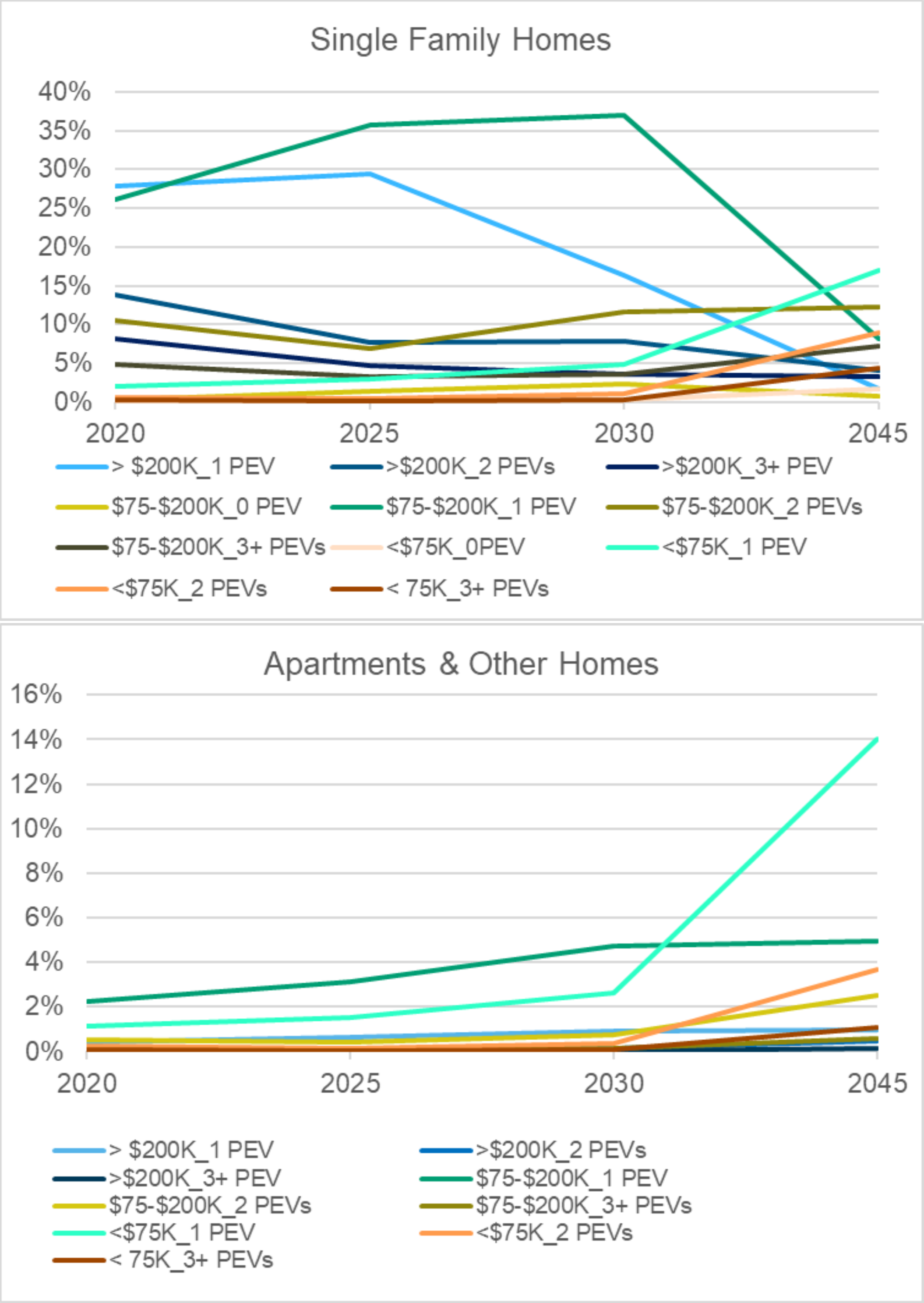

Figure 6.12. Proportion of households by PEV ownership and housing type

Figure 6.13 shows the type of ZEV allotted to households based on the allotment rule in Table 6.2. In our demonstration of the cost of fleet transition per the scenario of Tool 1, as households adopt their first ZEVs in the initial years (2020–2025), they are mainly allotted long-range PTs (long-range BEV PT, PHEV-80 PT, fuel cell PT) or mid-range BEV PCs. After 2025 as households in the high- and middle- income single-family categories start adopting the second ZEV in the household, once again long-range PTs are allotted to these households. Post 2030, when lower income households start entering the market and households start adopting multiple ZEVs, a wider variety of ZEV types are allotted in the cost comparison model.

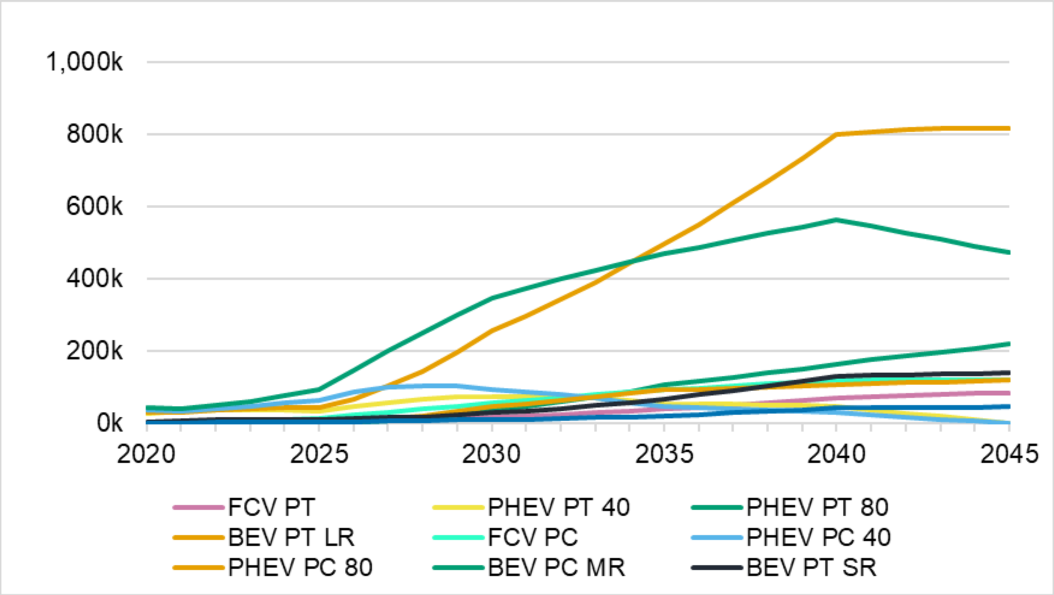

Figure 6.13. Type of ZEV allotted for TCO comparison. (PT, passenger truck; PC, passenger car; LR, long-range; MR, medium range; SR, short range)

The trend of capital cost differences between ZEVs and ICEVs that need to be incurred for transitioning to a 100% ZEV fleet in California corresponds to the vehicle adoption pattern observed in Figure 6.12 and Figure 6.13. The difference in upfront capital cost between ZEVs and ICEVs increases from 2020 to 2025 as more high- and middle-income households in California adopt their first ZEV. Considering the TCO of long-range ZEV PTs is higher than other categories of vehicles, the average capital cost (weighted) that has to be incurred to move to ZEVs is high. Beyond 2030 as lower income households start adopting ZEVs and detached home dwellers add two or more ZEVs to their fleet, the average capital cost difference between ZEVs and ICEVs lowers. Overall, we observe that over the years, although the average upfront annualized capital cost of ZEVs remains higher than comparable gasoline vehicles for all the household categories, it reduces on average by 81% from 2020 to 2045 in response to fall in cost of the ZEV technologies.

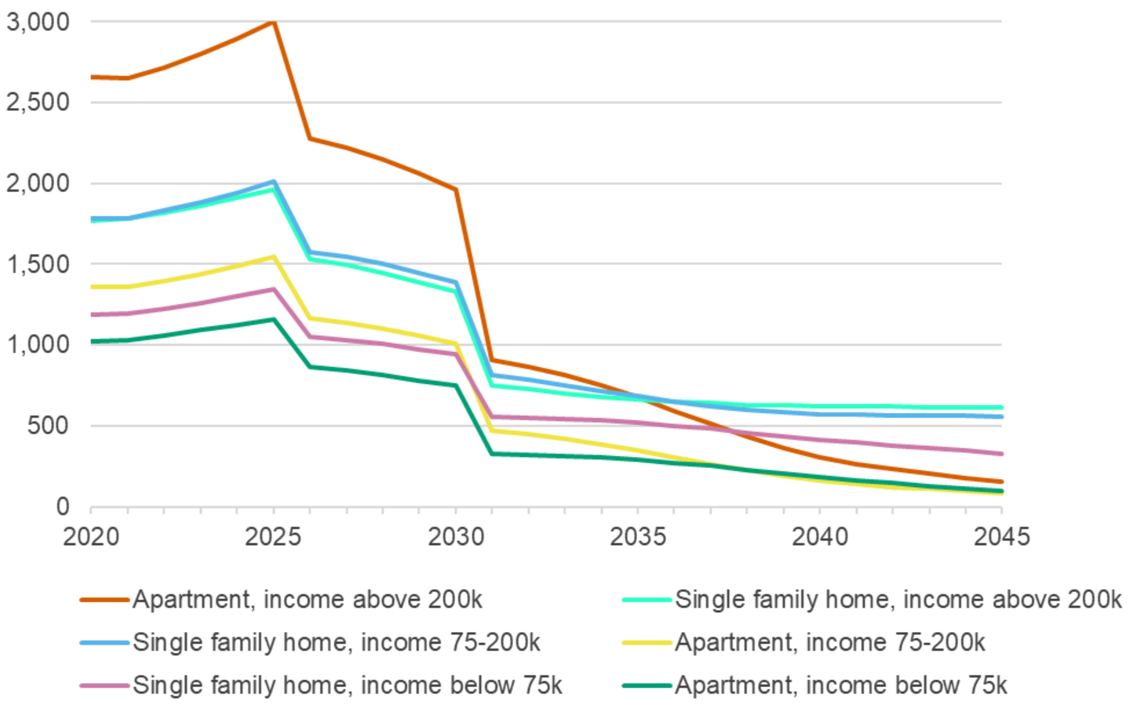

Figure 6.14. Average capital cost difference between a ZEV and an ICEV-fleet

On average the upfront capital cost associated with ZEV adoption is higher than ICEVs for the six household categories over the years. There will, however, be variation at the household level due to differences in their fleet size, number of PEVs in the household, and thereby the type of PEV allocated. Analyzing the proportion of households within each of the six categories that benefit from ZEV adoption in terms of capital cost, we observe in Figure 6.15 that the percentage of households benefiting from ZEV adoption compared to continuing with a comparable ICEV increases significantly beyond 2030. This trend occurs as the share of ZEV PCs, including short- and mid-range BEVs in the fleet, increases and the manufacturing cost of ZEVs drops while the cost of ICEVs increases due to tightening CAFE standards (assumed). Also, apartment dwellers tend to benefit more than detached-home owners in terms of capital cost differences because the latter only incurs the cost of installation of Level 2 chargers at home.

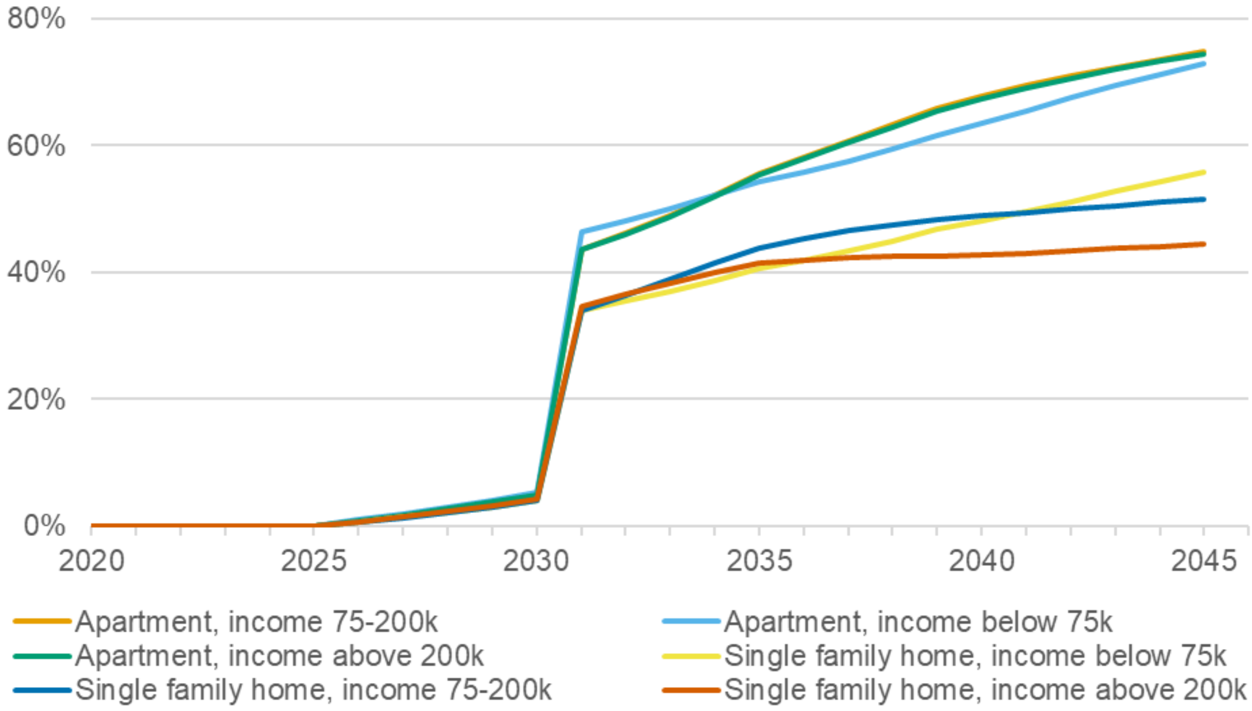

Figure 6.15. Proportion of household with capital cost benefits from purchasing ZEVs

In terms of operating costs, ZEVs have a lower cost of operation than gasoline vehicles, although the difference decreases across the years as gasoline vehicles become more fuel efficient as shown in Figure 6.16. Although gasoline prices go up in 2025 and 2030 compared to 2020, the gain in fuel efficiency potentially dampens its effect on fuel cost for ICEVs. Another possible explanation for the decrease in operating cost differences is the rise in the share of lower income households in the ZEV market. Lower income households tend to have lower annual VMT and thereby the gain from switching to ZEVs is potentially lower than high- and middle-income households. Also, as low-income households are more dependent on non-home charging options, the cost of charging in higher for these households.

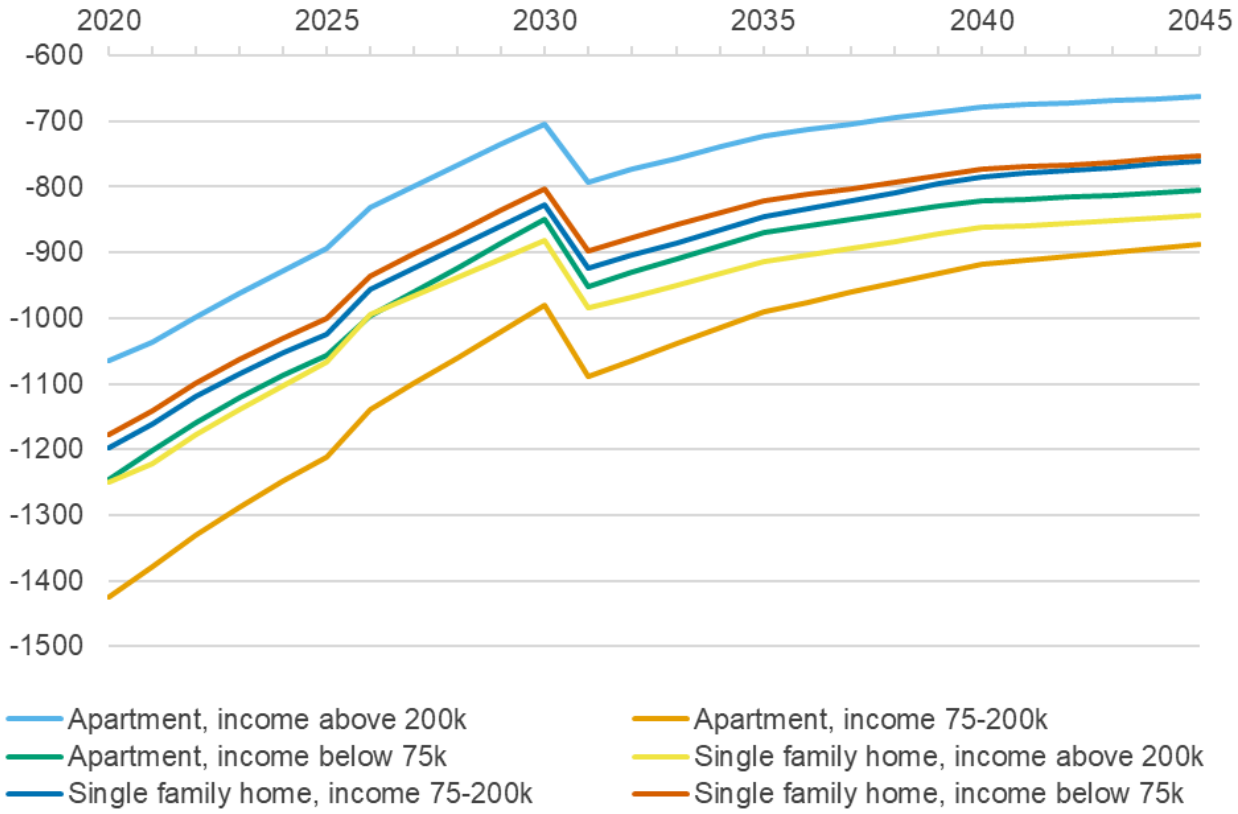

Figure 6.16. Average operating cost difference between a ZEV and an ICEV fleet

Finally, summing up the capital cost, operating cost, and resale value of a ZEV fleet for the six household categories, we observe in Figure 6.17 that at the fleet level, the average total cost of adoption of ZEVs is higher than persisting with a comparable ICEV fleet for the apartment-high income and detached home dwellers of all income categories until 2030. Low-income households, on the other hand, tend to have a favorable TCO even in the initial years due to allocation of used ZEVs in the scenario demonstrated here. Beyond 2030, the TCO of ZEVs falls as the capital cost of these vehicles falls and higher penetration leads to adoption of mid-range PEVs in the PC segment and shorter-range PTs. Cost parity is achieved between year 2030 and 2035 by all six household categories. Generally, as the low-income households, both apartment and detached-home dwellers, buy a lower share of new vehicles according to the vehicle allocation scenario demonstrated here, the cost of ZEV adoption for these categories of households is more favorable and these households reach cost parity earlier than high- and middle-income households.

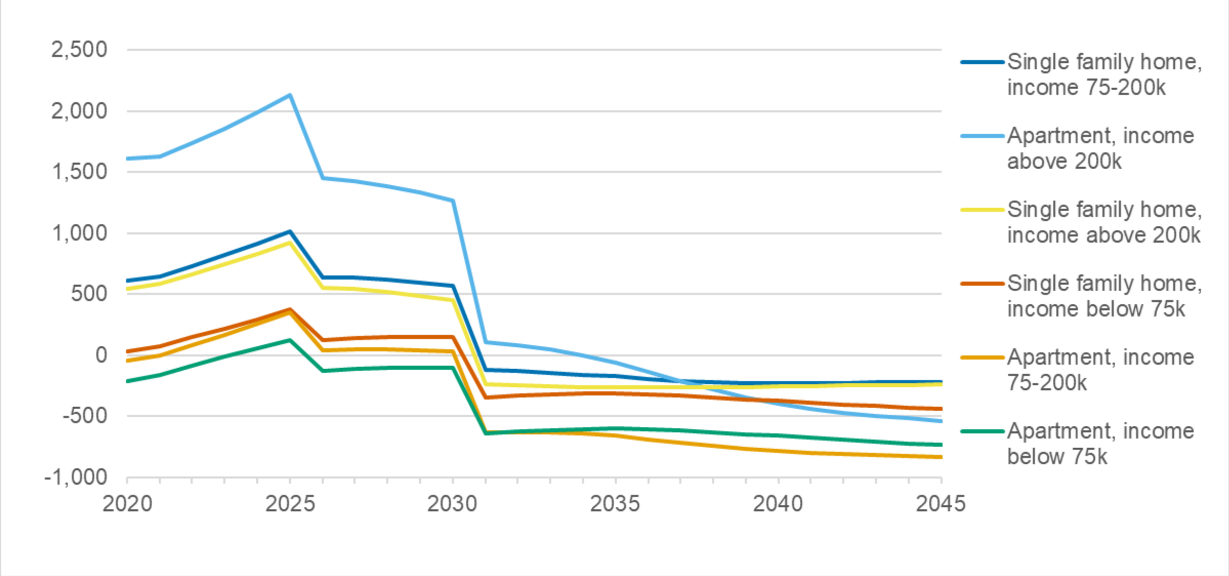

Figure 6.17. Average TCO difference between a ZEV and an ICEV-fleet

As in the case of capital cost, the TCO and thereby the total cost of adoption of ZEVs can vary at the household level. While some may benefit from electrification of their household fleet, others may not. As a result, the share of households in each of the six categories that benefit from switching to a ZEV rather than a comparable ICEV will vary over the years. As observed in Figure 6.18, in the initial years when the cost of ZEV technology is high and high- and middle-income households add their first long-range ZEV PT or the mid-range PC, the share of households benefiting from electrification falls for all six household categories. Post 2025, as the share of economical daytime workplace charging goes up and the upfront capital cost falls, the share of households benefiting from electrification rises. Beyond 2025, 45% to 65% of the households incur TCO benefits across the six household categories compared to 20% to 42% in the initial years.

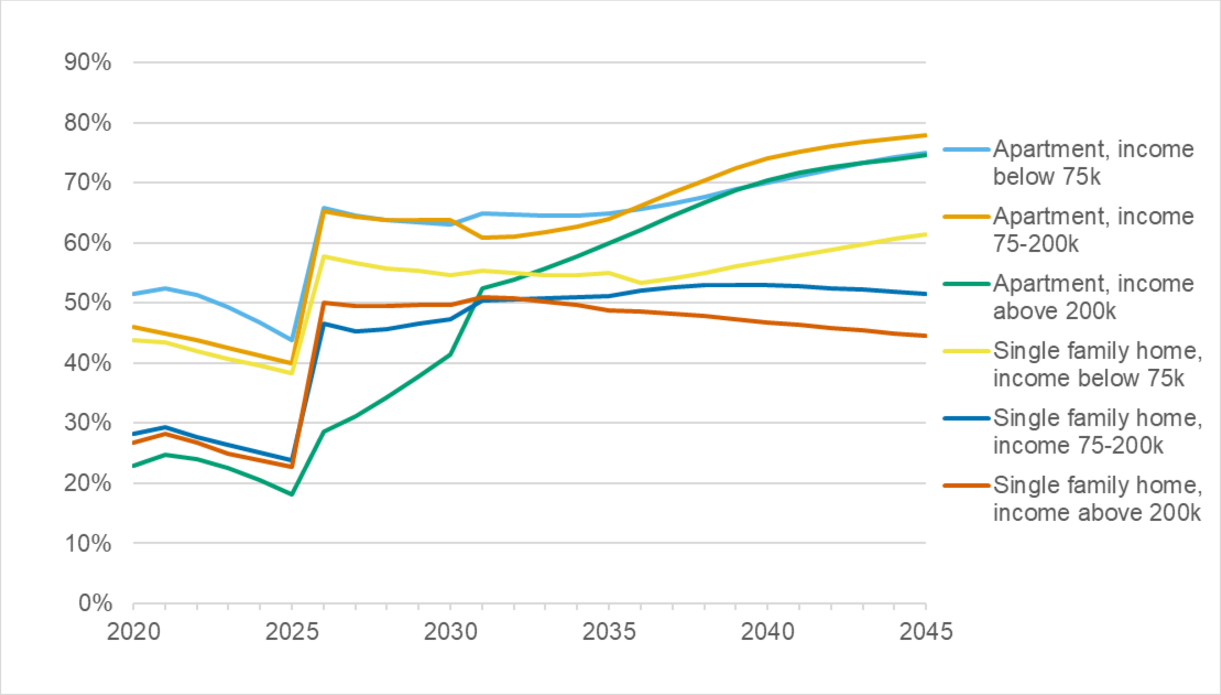

Figure 6.18. Proportion of household with capital cost benefits from purchasing ZEVs

6.2.3.1 Policy Implications of the TCO Modeling

The primary motivation behind the demonstration of a possible TCO scenario was to bring forth some of the important market characteristics and barriers that policymakers need to consider in transitioning the current California fleet to an almost 100% ZEV fleet (stock) by 2045. While the results will alter based on the ZEVs allotted, the share of new and used vehicles assigned to each household category, or with a change in the other TCO model assumptions, we believe that the policy-relevant points that are illustrated here will continue to hold.

First, ZEVs have been subsidized over the past decade by the federal and state government to encourage adoption. As the purchase price of ZEVs decreases due to improvements in battery technology or powertrain components, policymakers expect to be able to phase out these subsidies and incentives. However, as we observed in Figure 6.17 and Figure 6.18, cost parity is not achieved by most household types until 2030. Moreover, there will be some households at all time points who will continue to need incentives to adopt ZEVs as they do not benefit from switching to these vehicles, potentially due to their travel needs, access to charging facilities or other fleet characteristics.

Second, as our vehicle allocation scenario and TCO results indicate, low-income households would need access to cheaper used ZEVs in the market to be able to meet cost parity and replace their ICEVs with these vehicles. Thereby, to encourage electrification among the lower income households, a robust used car market for ZEV vehicles will be important. Moreover, as our comparative analysis of operating costs for ZEVs and ICEVs show, the cost savings from switching to ZEVs fall in the later years as low-income households adopting these vehicles are more dependent on non-home charging infrastructure. As charging at public infrastructure can be expected to remain more expensive than home charging, it is important to consider policies that will allow higher access to overnight/at-home charging for low-income households and apartment dwellers.

6.3 Discussion

6.3.1 Unknown Factors and Research Needs

One significant unknown involves the way vehicle ownership flows—both to the secondary market and in and out the state. We expect that a large transportation electrification policy gap between California and other states will create a price imbalance that may grow over time as used ZEVs flow out of the state while used ICEVs flow in to replace the disappearing new ICEV market.

New research is needed to establish the best policies regarding the secondary market and its impact on equity, the turnover of the new market, and interstate flows. The distribution of the used vehicles will also impact the demand for home and public charging needs.

This report supports the continuation of the current set of policies implemented by the state and suggests the need to keep and accelerate the incentives for purchasing new and used ZEVs and for installing home, work, and public charging infrastructure. This scenario analysis needs more development to fully understand which segment of the population will benefit, from a TCO perspective, from electrification during each time frame and which are the best options for policies to address the segments that may not benefit financially.

This section is based on the assumptions that vehicle ownership and vehicle usage will stay the same in the future. Ride sharing services and automation may change the need for vehicles without changing the basic associations between sociodemographic and vehicle ownership and usage presented in the analysis. Alternatively, new technologies and automation may change the relationship between vehicle ownership, vehicle usage, and sociodemographic characteristics. Further analysis is needed to explore the potential impacts of ride sharing and automation on electrification policies and infrastructure investments.

6.4 Equity

6.4.1 Equity and Environmental Justice

The shift to an electric vehicle fleet requires significant public investment and it is therefore important to make sure that all segments of society can benefit from this transition. The dissection discussion is limited to vehicle ownership and the transformation from internal combustion engines to ZEV vehicles and does not include discussion on other very important policies that are focused as substituting for vehicle ownership. Electric transportation reduces greenhouse gases which benefit everyone equally and reduces local air pollution in areas with high ZEV substitution. Our analysis does not include the secondary impacts of electric transportation, such as air quality impacts on the workforce; we focus only on vehicle ownership and the direct impacts on cost of transportation.

The main barriers for lower-income households to adopt ZEVs are purchase price, charging availability, and vehicle availability. Our initial TCO analysis shows that based on the current technologies the electrification of many vehicles will not benefit the buyers compared to equivalent ICEVs. In early years, the market is based on new vehicle purchases where most buyers are not benefiting (in terms of TCO) from having these vehicles. Used vehicles may offer better TCO performance but may have higher risk to the second owner in terms of unknown reliability. Policies that will extend the battery warranty may help low-income owners to take advantage of this market and of PEVs' low operating costs.

Direct incentives for new cars targeting lower-income buyers are usually not affecting households in disadvantaged communities who are very low income. In California, the income caps and additional incentives for lower income households were set in 2016 and modified again in 2019. The lower-income qualification is set at 300% of the federal poverty level (in 2020, $38,280 for a single person and $78,600 for a family of 4), and households that fall below this figure qualify for an additional $2,500 rebate. Unfortunately, households meeting these qualifications are not regular buyers of new cars, so while there are some who can benefit, the number of households applying for this rebate is quite low. Households receiving the standard state rebate in designated disadvantaged communities are often a sign of gentrification within that neighborhood more than increasing EV accessibility for low-income buyers. In March 2018, California added a rebate increase for state, federal, and local public entities who own and operate eligible vehicles in disadvantaged communities. While this doesn't increase access to electric vehicles for the community, it may help to increase electrification of miles travelled in the community, thereby addressing the local air quality concerns. Finally, in November 2020, California announced a new "cash-on-the-hood" point-of-purchase rebate of $1,500 available to any buyer of a new electric vehicle from a qualified dealer, regardless of income. The program is funded by utilities through Low Carbon Fuel Standard credits. But again, it applies only to new cars.

Home charging is expected to be the lowest cost option for PEV owners who can control their utility bill. This control allows for installing a Level 2 charger, installing solar panels, moving to time-of-use or PEV rates, etc., which are crucial to reducing operating cost and are highly correlated with ownership of detached housing, while renters or multi-unit dwellers have a much lower ability to control their utility rates, and therefore their operating costs. Installing public charging for overnight use is part of the solution; however, without control over their cost of charging, it may not be sufficient for many drivers. Fast charging can help for those who cannot charge every night but fast charging is currently more expensive than Level 1 or Level 2 charging and will not be an equivalent substitute. Wireless charging installation at multi-unit dwellings is one option being evaluated by utilities, however the price is still not regulated for all users.

Additional opportunities for fast electrification of transportation in disadvantaged communities, such as electric shared vehicles, electric transportation network companies, and electrified transit services are not included in our scenario modeling effort but can be important for lowering the cost of traveling while reducing the environmental impacts of transportation.

6.5 Key Policies

Studies that focus on the current ZEV market, together with our TCO analysis, suggest that incentives are going to be an important policy over the next decade and for some segments even longer. As the market shifts from early adopters to the main market, purchase cost becomes more important and incentives' impact on the market is higher. A combination of supply policies such as the ZEV mandate and demand policies such as monetary and non-monetary incentives will be crucial in meeting the policy goal. The ZEV mandate can be lower than the annual sales goals leaving room for the market preference to determine vehicle type and technology, but at the same time creating a minimum market share for each year. Monetary incentives will allow higher sale prices and help the OEMs and the buyers to reduce the cost of the market transformation. Future incentives should be streamlined to get the maximum effect by reducing the purchase price at the point-of-sale rather than at a later time. The incentives have higher impact on lower-income buyers or buyers of lower priced vehicles, but reducing the incentives for other segments may impact repeat buyers and slow down market penetration. Similarly, incentives for used EV buyers may also have a secondary impact on their residual value and on the repeat buyers and vehicle turnover rates. More research is needed to estimate the right amount of incentives as a function of the vehicle price, supply policies, sociodemographic, equity and the policy goals for market share. While our analysis includes only one scenario of vehicle types and drivetrains included in the ZEV mandate, future policies will have to support changes in technology and changes in consumer preference that are beyond the scope of this report. The cost of electrifying large platforms such as SUVs, pickup trucks and crossovers is higher than electrifying smaller sedans, and therefore supply has lagged behind the supply for smaller LDVs. However, the supply and demand for these vehicles should closely follow the supply for light-duty vehicles existing today. To reduce the dependency on long-range LDV BEVs and the dependency on home charging and DC fast charging, our scenario analysis includes PHEVs as part of the of the study. To maximize the impact of those vehicles we used a longer electric range than available on the market today. The success of plug-in hybrids will require new policies that include range end power specifications and perhaps performance based credits in order to achieve higher eVMT and low GHGs.

In addition to the need to subsidize or incentivize the purchase of new ZEVs, our scenario model shows that there is high investment needed to install charging infrastructure. We are not exploring the cost of upgrading the electric distribution network or increasing or changing generation. Our focus is only on the number of level two chargers and DCFC fast chargers required to support the light-duty vehicle private fleet electrification. We expect high demand for level 2 home charging that will require some level of support for low income buyers and for users who will have high upgrade costs to be able to install chargers.

Installation of charging at work correlates with the benefits of charging during the day and needs to be funded by the future benefits of the low cost of electricity during the day. Fast chargers are expected to have a low return on investment because of the low overall utilization rate, which will improve in later years. The cost of installing fast chargers will be determined by the public and a mix of new business models that will provide services to PEV users. The fast and full substitution of the ICE vehicle fleet to mostly PEVs in less than 20 years will require an accelerated ramp up of charging infrastructure that will peak around 2040 and will start dropping dramatically after 2045.

Level 2 home charging together with workplace charging and public charging will have to grow quickly to allow the market expansion, and with it the capacity and expertise in installing charging. However, this demand will peak in 2040 and therefore a policy is recommended to start overbuilding the charging capacity in early years to reduce the cost of a short peak demand and allow faster market grow for PEVs.

6.5.1 Light-duty Vehicle Policy Timeline

- 2020–2025
    - Incentives required to compensate for the price premium
    - Encouraging vehicle leasing to accelerate used car market
    - Access to at-home charging option for low-income and apartment dwellers
- 2025–2030
    - Incentives required by most household categories
    - Access to at-home charging option for low-income and apartment dwellers
- 2030–2035
    - Need for incentives to be targeted to encourage ZEV adoption among apartment dwellers and lower-income households.
    - Incentives required for used ZEV adoption
- 2035–2040
    - Key factor for TCO benefits in the low-income household category is the availability of used ZEVs
    - Incentives needed for used ZEVs
- 2040+
    - Incentives should be targeted to remaining 30% of the low-income groups to reach goal

6.6 5-Year Plan

Table 6.3 includes a summary of the results of this section. We divide the results into three categories: The first category are markers that are the basic assumptions in our scenario model links and that can help policymakers and planners check if the technology and similar external and internal factors meet expectations, or if any updates are needed for the policy. Higher price of batteries, for example, will require more subsidies or a slower adoption rate, while new vehicle or charger technologies that reduce TCO may accelerate the transition. The second category is barriers, with a focus on the change over time. Home charging, for example, is not a barrier today mostly because of self-selection of PEV buyers, but it will become a significant barrier in future years. Finally, the third category is the policies required to achieve the goals described in this scenario.

Table 6.3. Milestones Barriers and policies for 100% LDV electrification

	2020–2025	2025–2030	2030–2035	2035–2040	2040+
Technology and capital cost					
Markers: Battery price	$157–$161/kWh (for BEVs) $212/kWh (for PHEV PCs and PTs)	Average: $107/kWh (Min: $82/kWh; Max: $133/kWh)	Average: $87/kWh (Min: $62/kWh Max: $112/kWh)	Advancement in technology not included in this demonstration scenario	Advancement in technology not included in this demonstration scenario
Markers: Vehicle availability	Current market focus is on PCs and small PTs. Need mid- and long-range PTs to encourage 1st ZEV adoption.	1. Availability of a variety of vehicle models in both PC and PT segments 2. Longer range PHEVs introduced	1. Maturing secondary market with high supply of used PEVs from early adopters 2. ICEVs expensive if CAFE standards hold	1. Maturing secondary market with high supply of PEVs from early- and late-adopters 2. Mid-range ZEV PTs and PCs adopted in multiple ZEV households 3. Lower-range PHEVs start to phase out	1. Mature secondary market for ZEVs 2. Shorter-range PHEVs phased out 3. No new ICEVs available
Barriers: Cost	1. High ZEV price 2. Lack of mature secondary market for ZEVs 3. Low-income households dependent on non-home charging	1. ZEV price lowers but still high 2. About 50% of the market enjoys TCO benefits 2. Low PEV uptake among low-income as secondary market matures	1.Capital cost difference between ZEVs and ICEVs drops by 23%, but for approximately 95% of the market no capital cost benefits from switching 2. TCO benefits of low-income households depend mostly on used car availability	More than 50% of the market enjoys capital cost benefits but gain is lower for low-income households.	TCO benefits not enjoyed by 100% of the market

	2020–2025	**2025–2030**	**2030–2035**	**2035–2040**	**2040+**
Policies	1.Incentives required to compensate for the price premium 2. Encourage vehicle leasing to accelerate used car market 3. Access to at-home charging option for low-income and apartment dwellers	1. Incentives required by most household categories 2. Access to at-home charging option for low-income and apartment dwellers	1. Need incentives to be targeted to encourage ZEV adoption among apartment-dwellers and lower- income households 2. Incentives required for used ZEV adoption	1. Key factor for TCO benefits in the low-income household category is the availability of used ZEVs 2. Incentives for used ZEVs	Incentives should be targeted to remaining 30% of the low-income groups to reach goal
Market **Veh replaced** **1. Markers:** **Barriers** **Policies**	First and second vehicles in upper-income households with single-family homes. Very low among all others.	Most high-income households will have at least one ZEV. First vehicle in more middle-income households and apartments. Slow expansion in lower-income households. B: Lower-income households and apartments will require non-home charging infrastructure.	Most middle-income single-family home households will own at least one ZEV. More apartment dwellers adopt the first ZEV. More second and third ZEVs for all groups. Slow adoption among single-vehicle households. B: Fully developed secondary market will be vital to the continued electrification of the fleet.	Most expansion of ZEV ownership will be among low-income and single-vehicle households. High-income households may use FC vehicles to replace the last ICEV.	All new vehicle sales in this period will be ZEVs. By 2045, almost all vehicles will be ZEVs and most ZEV sales will go to replacing retired ZEVs. B: ICEV holdouts, likely either very low mileage or cost-insensitive.

	2020–2025	2025–2030	2030–2035	2035–2040	2040+
Infrastructure	Because of self-selection most buyers can charge at home Workplace charging is mostly free Limited DC fast is not an issue as most households have additional vehicles	First PEV only households require expanded DCFC Network and dependable charging infrastructure Public investment may be needed to close service gaps.	Grid becomes cleaner during the daytime, and charging at work becomes a priority. Increased number of chargers per vehicle to support V2G.	Rapid infrastructure buildup to support full fleet electrification and V2G. A dependable and full coverage off hydrogen station will have to precede high market share.	Shift from rapid infrastructure buildup to maintenance.
Buyers, awareness, and preferences	Lower level of awareness reduces the demand for PEVs	Increasing awareness and vehicle models	Widespread awareness and trust in the technology, as well as sufficient variety of makes and models available	PEV rejectors have to choose FCEVs or keep driving ICEV that are at least 5 years old	PEV rejectors have to choose FCEVs or keep driving ICEV that are at least 5 years old

6.7 Conclusions

To meet the goals of electrifying the light-duty vehicle fleet by 2045 the market share of plug-in vehicles has to grow more quickly than the drop in cost and pricing expected to happen in the next 15 years. The success of the scenario presented is based on three types of policies: 1) supply based policies such as the ZEV mandate that will ensure market supply of a variety of vehicle types and technologies; 2) demand based policies that enhance the demand for these vehicles, including direct monetary incentives and non-monetary incentives, and policies that focus on market turnover including encouraging second-hand buyers and vehicle retirement plans; and 3) charging infrastructure build-up policies this will assure the necessary charging infrastructure will be ready and will not slow down the market growth. More work is needed to quantify the required incentives for private and fleet buyers, for the secondary market, and future markets. This study did not include a thorough analysis of interaction effects with other policies in the state of California or externally. We also did not cover the impact of market changes and priority changes in other states and the federal government.

7 Medium- and Heavy-Duty Vehicles

Out of approximately 26.6 million registered vehicles in California, roughly 1.5 million (6.2 percent) are medium- and heavy-duty trucks (Class 2b-8). Despite their small share of the vehicle population, trucks are responsible for 70% of the smog pollution and 80% of diesel particulate matter (PM) emissions. By themselves, heavy-duty trucks emit over 22 percent of CO_{2e} from on-road transportation in California, which illustrates the importance of reducing GHG emissions from medium- and heavy-duty vehicles.

Regulations governing GHG emissions for medium- and heavy-duty vehicles at the federal level and in California were adopted barely a decade ago. In 2011, the U.S. EPA and the National Highway Traffic Safety Administration (NHTSA) jointly adopted the first federal GHG emission and fuel economy standards for heavy-duty engines and vehicles, referred to as the federal Heavy-Duty GHG Phase 1 regulation. It requires both engine and vehicle manufacturers to use more efficient components and systems. The federal Phase 1 standards took effect with model year (MY) 2014 for tractors, vocational vehicles, heavy-duty pick-up trucks and vans (PUVs) and the engines powering such vehicles, but they did not set include trailers. In 2013, CARB approved California Phase 1 GHG regulations that were substantially identical to the federal Phase 1 regulations. This gave California the authority to certify new engines and vehicles to the Phase 1 standards, and to enforce these standards. However, Phase 1 GHG standards were not sufficient to offset the projected growth in medium- and heavy-duty truck VMT because without stricter standards, the GHG emissions from these vehicles would increase each year starting in 2023.

To keep heavy-duty truck GHG emissions declining, a second phase of GHG standards was therefore needed. CARB staff worked closely with U.S. EPA and NHTSA over the past several years on developing Phase 2 GHG standards. On October 25, 2016, U.S. EPA and NHTSA jointly adopted the federal Phase 2 standards. These standards follow the same regulatory structure as the federal Phase 1 standards. They set GHG emission standards for tractors, vocational vehicles, and PUVs, and separate engine standards for the engines used in tractors and vocational vehicles. In addition, they created federal emissions requirements for trailers hauled by heavy-duty tractors. The federal Phase 2 standards are more technology-forcing than the federal Phase 1 standards, as they require manufacturers to improve existing technologies or develop new ones. The progressively more stringent Phase 2 standards are phased-in from 2021 to 2027 for tractors, vocational vehicles, and PUVs, and from 2018 (2020 in California) to 2027 for trailers. To minimize the regulatory burden on manufacturers, California aligned in 2019 with the federal Phase 2 standards in structure, timing, and stringency, with some minor differences [219], [220].

One key characteristic of the heavy-duty vehicle sector is its multifaceted heterogeneity, which contributes to challenges addressing its pollution. Aspects of this heterogeneity include vehicle attributes (e.g., their gross vehicle weight and their configuration), industry affiliation, travel characteristics (e.g., trip length, tour structure and drive cycle), and ownership status (from individual ownership to large fleets owned and operated by large firms).

To better understand some facets of this diversity (industry served and commodities hauled), we first performed a simple analysis of trip length distributions by commodity types using the California Statewide Freight

Forecasting and Travel Demand Model (CSF2TDM) before reviewing selected funding programs for medium- and heavy-duty trucks. We then applied some of the insights from this analysis to four subcategories of trucks—drayage trucks, long-haul trucks, trucks from weight classes 2b–3, and construction trucks—to outline strategies for contributing to the state's carbon-neutrality goal. We chose these four subcategories because they cover a wide range of truck categories, some of which have been targeted by specific regional and statewide policies. They also illustrate the diversity of the medium- and heavy-duty vehicles sector.

This section does not discuss zero-emission (ZE) technologies for buses because of time limitations. Most buses will be electric by 2045 if current policies are continued (in the BAU trajectory, 96.5% of transit buses albeit only 1.9% of other buses will be electric by 2045) because the duty cycle of transit buses is well adapted to ZE technologies. Transit buses will most likely be the first among HD vehicles to deploy ZE technologies, so we are focusing instead on other categories of HD vehicles, where additional policies and incentives will be needed to foster the adoption of ZE vehicles and equipment. We acknowledge, however, the importance of transit buses in spearheading ZE technologies for HDVs, and their role in developing the ZE infrastructure in urban areas.

We note that Executive Order N-79-20, which sets a goal for 100 percent of zero-emission vehicles for in-state sales of new passenger cars and trucks accounts for the difficulty of reaching this target for all trucks. It also sets a target of 100 percent sales of ZE drayage trucks by 2035.

7.1 Trip Length Distribution Analysis

Truck activity varies significantly by size and affiliated industry. For example, medium-duty trucks typically travel shorter distances than heavy-duty trucks. In addition, trip-length patterns associated with the truck movements of different commodity groups are distinct due to the types of facilities and markets they serve. Knowing truck travel characteristics is useful to understand which zero-emission (ZE) technology is more suitable (e.g., battery electric (BE) or fuel cell electric (FCE)) for different industries.

CSF2TDM was used to analyze the trip-length characteristics of freight trucks by commodity hauled. CSF2TDM organizes trucks in four gross vehicle weight rating (GVWR) -based categories: 8,500–14,000 lbs., 14,001–26,000 lbs., 26,001–33,000 lbs. and >33,000 lbs. In CSF2TDM, commodities are grouped into 15 categories. CSF2TDM also includes a passenger vehicle model and assigns both passenger vehicles and trucks to its network to capture congestion effects on trip length and trip duration.

CSF2TDM has two modules for estimating freight and non-freight truck activity in California. Freight truck trips are defined as those involving commodity movement between firms that were captured by the Commodity Flow Survey (CFS), but they do not include trips within a firm's network, such as trips between a firm's own distribution center and its retail locations. Hence, non-freight trips capture the residual truck trips, which comprises all trips not involving commodity movement as well as intra-firm freight trips. In our analysis of truck trip lengths, we assumed that most interstate trips in and out of California are performed by trucks registered outside California and analyzed only trips with both ends located within California, as these were assumed to be primarily performed by in-state registered trucks. The total number of trips with origins and destinations inside California for freight and total (the sum of freight and non-freight) truck trips based on CSF2TDM truck classes are shown on in Figure 7.1. More than half (52.8%) of daily freight trips and approximately 21% of total trips are performed by Class 8 trucks, while almost one third (29.6%) of freight trips and half of total trips are performed by trucks from Classes 4 to 6. Approximately 10% of freight trips and 7.5% of total trips are performed by Class 7 trucks, with the remaining trips performed by trucks in Classes 2b-3. The shares of Class 2b-3 and Class 4 to 6 trucks are higher for total and non-freight trips compared to freight trips, because of the much higher percentage of non-freight (service) trips performed by those smaller trucks compared to other truck classes. GVWR Class 8 are mostly semis but also drayage trucks, while GVWR Classes 4, 5, and 6 are single-unit trucks that mostly take shorter trips in urban areas.

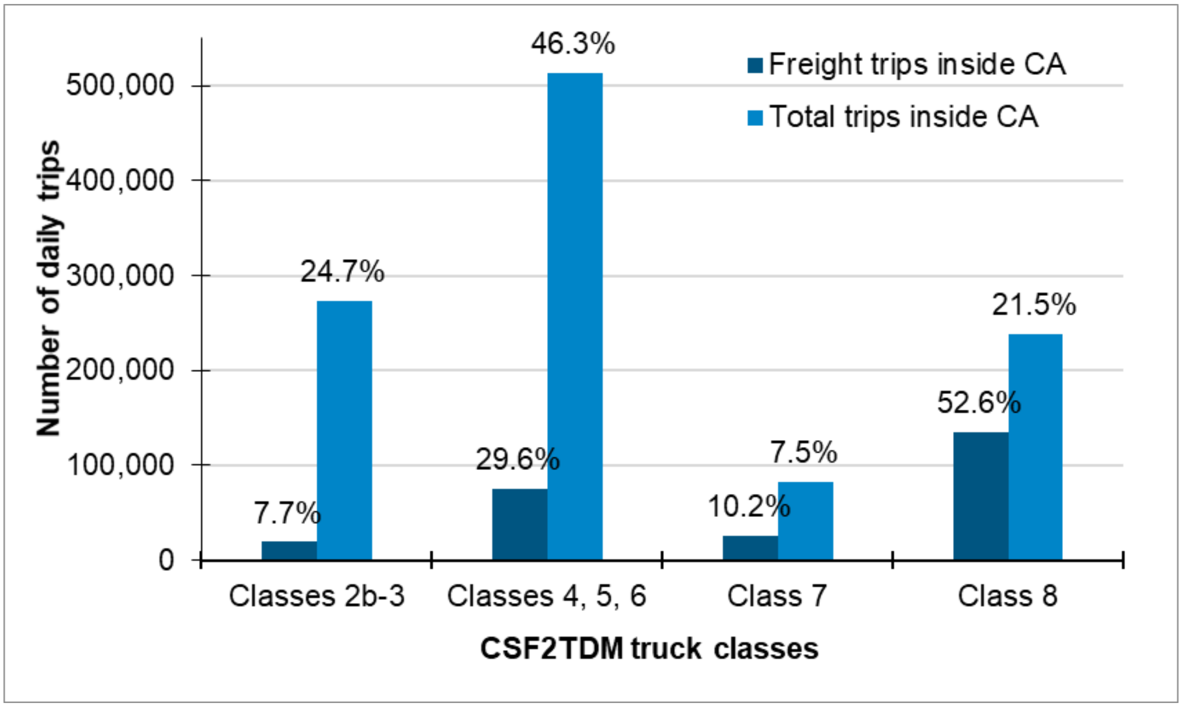

Figure 7.1. Daily Truck Trips by CSF2TDM Truck Class for 2020 (Source: CSF2TDM for trips starting and ending within California. Classes 2b-3: 8,500 to 14,000 lbs.; Classes 4, 5, 6: 14,001 to 26,000 lbs.; Class 7: 26,001 to 33,000 lbs.; Class 8: >33,000 lbs.)

To describe in more detail the freight trips in each of the four CSF2TDM truck classes above, trip-length statistics for the CSF2TDM truck classes are shown on Figure 7.2. We see that the trip length and standard deviation of truck Classes 2b–7 are similar, with an average of 55–60 miles and a standard deviation of 170–190 miles. However, the average trip length of Class 8 trucks is approximately double that of Classes 2b–7, with an even larger standard deviation, which shows a lot of variability. This reflects that many class 8 trucks are semis engaged in long haul, but also tens of thousands of drayage trucks whose trips are local and therefore much shorter. In addition, Class 8 trucks have a greater payload capacity than Class 2b–7 trucks, which are mostly used for shorter trips for more flexible and faster operations.

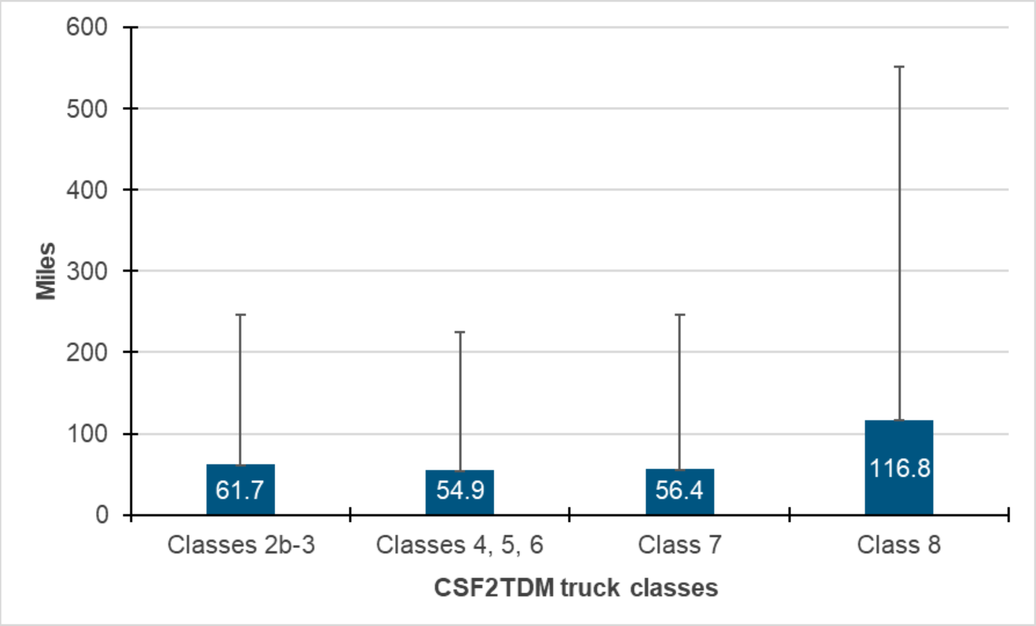

Figure 7.2. 2020 Average Trip Length by CSF2TDM Truck Class (I-bars indicate standard deviation.)

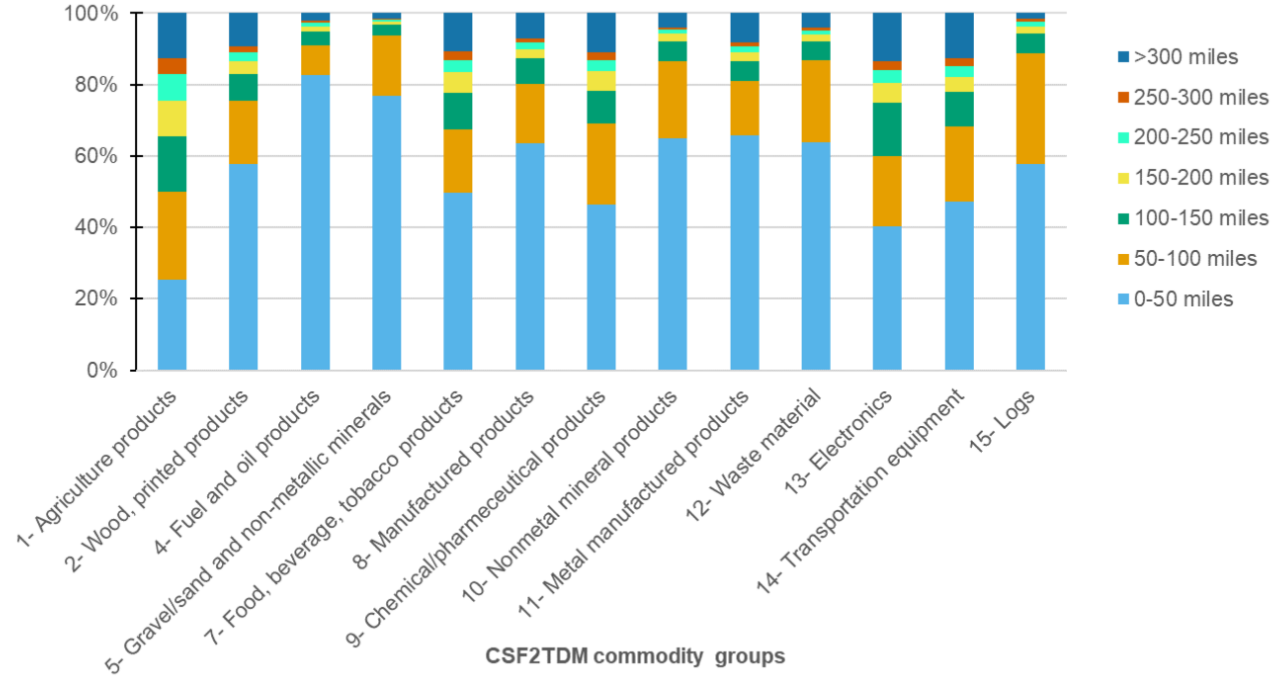

Figure 7.3. 2020 Trip Length Distribution by CSTDM Commodity Groups and Truck Class

Figure 7.3 shows the proportion of trip lengths for different commodity groups, with trip lengths binned into seven contiguous categories in 50-mile increments. Note that data for two commodity groups—3 (crude petroleum,) and 6 (coal/metallic minerals)—are not shown on Figure 7.3 because these commodities are transported exclusively by rail and pipelines. Moreover 90% of trips for commodity groups 4 (fuel and oil products) and 5 (gravel/sand and non-metallic minerals) are under 100 miles. Owing to the types of facilities served in these industries, the trips associated with these two commodity groups are expected to be mostly line haul in nature without multiple stops or tour behavior. Hence, the required range between consecutive refueling/recharging events should be at least twice the trip distance to account for return trips, assuming a refueling/recharging station is at the base. Keeping this in mind, current BEV and FCEV technology should therefore be adequate for over 90% of trips for trucks that primarily haul commodities from these two groups.

Indeed, according to the US Department of Energy (DOE) (Jason et al. 2019), the current range of Class 8 BEV trucks is between 124 and 250 miles (e.g., BYD 8TT and Peterbilt Model 579), although it is projected to increase to 500 miles by 2050. The current range for Class 8 FCEVFCEV trucks is 300 miles (Toyota Project Portal drayage), but it is projected to reach 600 miles by 2030, and 750 miles by 2050.

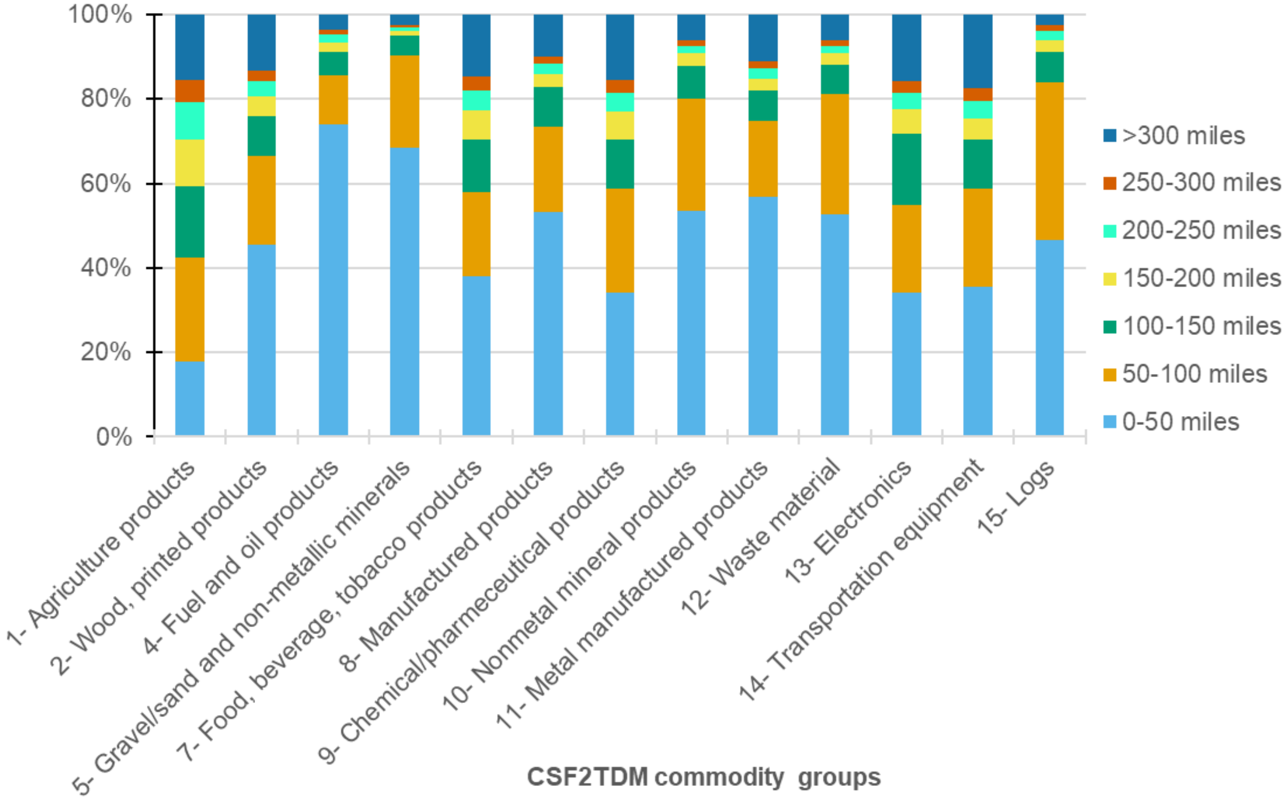

Figure 7.4. 2020 Trip Length Distribution by CSTDM Commodity Groups for Class 8 Trucks

As mentioned above, the trip length of trucks in Classes 2b–7 have similar characteristics, with trips typically under 200 miles. As a result, these trips could be performed with current alternative fuel trucks, but they should be analyzed in depth (for example using GPS data if available) to understand possible tour-based behavior in specific industries that could create refueling constraints.

Trip length for Class 8 trucks by commodity group is shown on Figure 7.4. Class 8 trucks have the highest number of trips, longest average trip distance, and largest variation in trip distance compared to the other CSF2TDM truck categories. As shown on Figure 7.4, more than 80% of trips for commodity groups 4, 5 and 15 are shorter than 100 miles so they could be performed by current BEV Class 8 trucks [221]. For other commodity groups, FCEVFCEV trucks would be much more appropriate.

7.2 Achieving LC1 Targets for Specific Truck categories

In this section, after summarizing current programs targeting all or most ZE trucks, we focus on four subcategories of trucks (drayage trucks, long-haul trucks, trucks in weight classes 2b–3, and construction trucks) because they are among the main contributors of GHG and air pollutant emissions, and to illustrate the diversity of issues and vehicles to consider when planning a transition to ZE trucks.

7.2.1 Funding programs for medium- and heavy-duty vehicles

7.2.1.1 Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program

The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) is the cornerstone of CARB's advanced technology heavy-duty incentives. It has been providing funding since 2010 to support the long-term transition to ZEVs in the heavy-duty market, and investments in other emerging clean technologies to achieve substantial greenhouse gas reductions and help meet health-based ambient air quality standards. Voucher incentives complement other programs in CARB's heavy-duty funding portfolio by providing a streamlined application process without requiring scrapping of an existing vehicle. HVIP is a unique project in the CARB portfolio. As the only project that exclusively supports on-road heavy-duty advanced technologies with high adoption barriers, it provides the bridge between demonstrations and pilots to the scrap-and-replace programs. HVIP also plays an important role in preparing the market for regulations by increasing market adoption and decreasing vehicle costs prior to regulatory deadlines such as those for the Innovative Clean Transit rule and Advanced Clean Trucks rule. HVIP supports early commercial deployment of eligible zero- and near zero-emission trucks and buses with point-of-sale incentives to reduce the incremental cost of advanced technologies. Priority is given to projects that benefit disadvantaged communities with increased incentives for fleets located in disadvantaged communities. The voucher is redeemed at the time the truck or bus is purchased or leased from a registered dealer; the registered dealer works with the buyer to complete the voucher request form when the vehicle is ordered [222].

7.2.1.2 Carl Moyer Memorial Air Quality Standards Attainment Program

The Carl Moyer Memorial Air Quality Standards Attainment Program (Carl Moyer Program) has helped reduce smog-forming and toxic emissions throughout California since 1998. The Carl Moyer Program is a voluntary grant program that seeks cost-effective surplus emission reductions to be credited toward California's legally enforceable obligations in the State Implementation Plan (SIP)—California's road map for attaining health-based national ambient air quality standards. Emission reductions must be permanent, surplus, quantifiable, and enforceable to meet the underlying statutory provisions and be SIP-creditable [223]. It is funded through CARB in partnership with local air districts, which administer the grants and select eligible projects. CARB works with local air districts and other stakeholders to set guidelines to ensure that the program reduces pollution earlier and/or beyond what is required by existing regulations [224]. The program provides incentives to replace, repower, or convert older, more-polluting vehicles and engines, paying up to 85% of the cost to repower engines and up to 100% to purchase a retrofit device. As of 2020, it has provided almost $1 billion in grants.

7.2.1.3 VW Mitigation Trust

The Volkswagen (VW) Mitigation trust was established to mitigate the diesel NO_x emissions caused by VW, which programmed the emission controls of turbocharged direct injection diesel engines to activate during laboratory emissions testing to meet US standards, when in fact NO_x emissions of these engines were 2 to 3 orders of magnitude higher during real-world driving. The state of California filed its Beneficiary Mitigation Plan with the fund administrator of the VW Diesel Environmental State Mitigation Trust in June 2018. A total of $423M will be available to California. Under the proposed plan, grants will be available to replace or repower vehicles with new diesel, alternative fuel, or all-electric vehicles or engines. Most of the funding ($220 million) will go toward zero-emission buses and large and medium trucks, with $90 million for Class 8 and port drayage trucks. At least 50% of the eligible VW Environmental Mitigation Trust funds is expected to benefit disadvantaged or low-income communities. Scrappage is almost always required. Implementation guidelines for disbursement of California's VW Environmental Mitigation Trust funding have been developed by individual air quality control districts. All programs are expected to terminate by May 2028 [225].

During 2019 and 2020, in addition to $10M for light-duty zero-emission infrastructure (hydrogen and electric charging stations), funding was allocated across four categories of projects: 1) Combustion freight and marine projects ($30M); 2) Zero-emission freight and marine projects ($35M); 3) Zero-emission transit, school, and shuttle buses ($65M); and 4) Zero-emission Class 8 and Port drayage trucks ($27M).

7.2.1.4 California's Truck Loan Assistance Program

CARB also started in 2009 a Truck Loan Assistance Program to help small-business fleet owners affected by CARB's Truck and Bus Regulation [226] to obtain financing for upgrading their truck fleet to newer trucks if they qualify and are unable to get traditional financing. This program is implemented in partnership with the California Pollution Control Financing Authority (CPCFA) from California's Treasurer's Office. This program is available for businesses with 10 or fewer heavy-duty trucks subject to the In-Use Truck and Bus Regulation at the time of application, with 100 or fewer employees, and $10 million or less in annual revenue averaged over three years.

7.2.2 Drayage Trucks

7.2.2.1 Drayage Trucks and Air Pollution

As of 2019, there were approximately 18,250 trucks in the Ports of Los Angeles and Long Beach drayage trucks registry (PDTR); registration in the PDTR is a necessary requirement to operate in the San Pedro Bay Ports (SPBP) complex, which is the largest container port complex in the US. Prior to clean truck regulatory and incentive programs targeting drayage trucks, the latter were typically older and more polluting than long-haul trucks [227]. By 2019, trucks registered in the PDTR were much cleaner than were when the Clean Air Action Plan was implemented in 2006; 56% of these trucks met 2010 EPA diesel engine emission standards, and the remaining were compliant with the 2007 EPA diesel engine emission standards. While most drayage trucks serving the SPBP have diesel engines, liquefied natural gas (LNG) trucks made ~4% of terminal calls in 2019. Compared to 2005, emissions from drayage trucks were cut by 96% for $PM_{2.5}$ 78% for NO_x, and 20–22% for CO_2, although they still emit substantial amounts of air pollutants and large volumes of CO_2. They also contribute to traffic congestion (particularly in the I-710 corridor), road noise, and accidents.

Table 7.1. Drayage Truck Emissions

	Vehicle miles traveled (million)	PM2.5	DPM	NOx	SOx	CO	HC	CO2e
Port of Los Angeles (2019)								
On-Terminal	6.51	0.4	0.4	183	0.4	112.4	9	40,798
On-Road	209.95	8.2	8.2	1,198	3.4	94.9	24.3	337,217
Total	216.46	8.5	8.6	1,382	3.8	207.3	33.3	378,015
Port of Long Beach (2019)								
On-Terminal	5.24	0.3	0.3	160	0.3	95.9	8	35,239
On-Road	169.51	6.6	6.6	967	2.7	75.6	19	271,865
Total	174.74	6.9	7	1,127	3.1	171.6	27.7	307,104

Notes. Emissions of all pollutants are in tons. $PM_{2.5}$: fine inhalable particles, with diameters that are generally up to 2.5 micrometers; DPM: diesel particulate matter; NO_x: nitrogen oxides; SO_x: sulfur oxides; CO: carbon monoxide; HC: hydrocarbons; CO_{2e}: number of metric tons of CO_2 emissions with the same global warming potential. Source: Port of Los Angeles, Air Emissions Inventory – 2019; Port of Long Beach, Air Emissions Inventory – 2019

The third-largest California port, the Port of Oakland, has also seen substantial reductions in air pollutant emissions from drayage trucks since 2005 (78% reduction for $PM_{2.5}$ and 31% for NO_x, for 2017), although these reductions were slightly smaller than those at the much larger SPBP complex.

7.2.2.2 Selected Past and Current Policies

7.2.2.2.1 California

All drayage trucks,, defined as on-road diesel-fueled heavy-duty Class 7 or 8 vehicles (i.e., vehicles with a GVWR over 26,000 lbs.) that transport cargo to or from a California port or a California intermodal yard, have to abide by California's drayage truck regulation [228]. In addition to listing documents that need to be available from the driver of the vehicle if requested by enforcement personnel, this regulation requires that: 1) drayage trucks be registered in the drayage truck registry; 2) all emission-control technologies on drayage trucks be installed and working properly; and 3) drayage trucks comply with the emission standards summarized in Table 7.2.

Table 7.2. Summary of California's Drayage Truck Regulation

Truck Engine Model Year	Emission Requirement
Class 8 (GVWR>33,000 lbs.)	
1993 and older	Prohibited
1994 to 2004	Reduce PM emissions by 85%[a], and after December 31, 2013, meet 2007 engine emission standards
2005 and 2006	After December 31, 2012, reduce PM emissions by 85% and after December 31, 2013, meet 2007 engine emission standards
2007 to 2009	After December 31, 2022, meet 2010 engine emission standards
2010 and newer	Fully compliant
Class 7 (GVWR 26,001 to 33,000 lbs.)	
2006 and older while operating in the South Coast Air Basin	Reduce PM emissions by 85%[a]
2006 and older	After December 31, 2013, meet 2007 engine emission standards
2007 to 2009	After December 31, 2022, meet 2010 engine emission standards
2010 and newer	Fully compliant

Source: https://ww2.arb.ca.gov/our-work/programs/drayage-trucks-seaports-railyards

[a]: Compliance methods may include the installation of a California Air Resources Board (CARB)-verified level 3 diesel particulate filter or operating a truck with an engine that meets or exceeds 2007 emission standards. Starting on January 1, 2023, drayage trucks must comply with the Truck and Bus Rule.

Some Class 7 and 8 trucks are exempt from this regulation (although all are required to have 2010 engines by 2023), including unibody vehicles that do not have separate tractor and trailer, such as fuel delivery vehicles, concrete mixers, logging trucks that haul only logs, vehicles using a power take off (PTO) with a hydraulic motor or blower, and on-road mobile cranes.

Starting January 1, 2023, drayage trucks are subject to the Truck and Bus Regulation (Title 13, California Code of Regulations, section 2025).

Idling by diesel trucks is a substantial source of pollution. To reduce emissions from idling trucks at port terminals, California Assembly Bill (AB) 2650, which was passed in 2002, required marine port terminals above a certain size (in this case those of Los Angeles, Long Beach, and Oakland) to either extend their hours of operation for truck pick-ups or deliveries, establish an appointment system for drayage trucks, or otherwise reduce trucks queuing at terminal gate entries. However, Giuliano and O'Brien (2007) found no evidence that the appointment system at the SPBP reduced queuing at terminal gates and heavy-duty truck emissions, partly because of how this system was put in place, and partly because of a lack of data. For the authors, this outcome showed "the pitfalls of imposing regulations that seek to indirectly achieve environmental policy objectives."

In 2003-04, CARB adopted two idling-related Air Toxic Control Measures (ATCMs), one for commercial vehicles and the other for buses. The former limits HDD diesel truck idling to 5 minutes, except for trucks certified to clean idle standards. These ATCMs underwent a review in 2020 to assess the health benefits of these measures and whether or not they should be strengthened [229].

To reduce air pollution from the over 18,000 drayage trucks serving the SPBPSPBP, the Ports of Los Angeles and Long Beach in 2008 launched the Clean Trucks Program (CTP). It is a key component of the Clean Air Action Plan, which was jointly adopted in 2006 by the Ports of Los Angeles and Long Beach. The CTP created three deadlines. First, on October 1, 2008, it banned all pre-1989 trucks from entering the SPBP. Second, starting on January 1, 2010, all 1989–1993 trucks were banned along with the 1994–2003 trucks that had not been retrofitted; in addition, trucks whose engines did not comply with the 2007 emission standards established by CARBCARB and the US EPA were subject to a $35 fee per 20-foot equivalent container effective February 2009. Third, after December 31, 2011, trucks not complying with 2007 engine emission standards were banned from entering the SPBP. In addition, trucks serving the SPBP must be operated by drivers who meet security requirements. These trucks are required to be equipped with radio frequency identification (RFID) tags, and they must be registered with the PDTRPDTR, a database that centralizes information on truck age, model year, engine year, and fuel type [230].

In 2017, the SPBP adopted the Clean Air Action Plan Update, which also targeted drayage trucks. It allowed trucks already registered in the PDTR that are current in their annual registration fees and comply with CARB's drayage truck regulation to continue serving the ports. However, trucks registered in the PDTR after October 1, 2018 must be model-year 2018 or newer. It also proposed creating a fee on all trucks that enter marine terminals, with exemptions for trucks that meet near-zero or zero emission criteria [231].

A loan program was put in place in Oakland for truckers to retrofit their vehicles, but it led to financial difficulties for truckers, and approximately one-quarter of those who participated filed for bankruptcy [232], so loan programs may not be adequate to help independent drayage truck owners purchase zero-emission vehicles.

The four incentive programs mentioned above (HVIP, Carl Moyer, grants from the VW Mitigation Trust, and California's Truck Loan Assistance Program) apply to drayage trucks, but they will likely need to be supplemented if the ambitious targets for ZE drayage trucks are to be achieved.

7.2.2.2.2 United States

To avoid the political controversies that surrounded the components of the Clean Air Action Plan at the Ports of Long Beach and Los Angeles, some ports around the country adopted voluntary control measures. Norsworthy and Craft (2013) [227] analyzed voluntary programs put in place by the Virginia Port Authority, the South Carolina Port Authority, and the Port of Houston Authority. They found emission reductions ranging from 1% to 4%, which compares to potential reductions ranging from 12 to 15% for PM and from 31 to 34% for NOx.

Also of interest is the Hunts Point Clean Trucks Program, which was launched in 2012 by the New York City Department of Transportation to retrofit, replace, or scrap polluting heavy-duty diesel trucks from the South Bronx and NYC. Since its start, the program has helped replace 592 diesel trucks from the South Bronx business communities of Hunts Point and Port Morris, reducing PM NO_x emissions by 96% and NO_x by 83% compared to the original trucks [233]. Building on this success, the NYC Clean Trucks Program offers rebate incentives to replace older, polluting diesel trucks from Class 4 to Class 8 with new all-electric or EPA-compliant alternative fueled (compressed natural gas (CNG), diesel-electric hybrid, diesel plug-in electric hybrid) and diesel trucks. In particular, it targets Class 8 diesel trucks used for local goods movement and port drayage trucks with 1992–2009 model-year engines [233].

On July 14, 2020, 15 states including California and the District of Columbia signed a memorandum of understanding (MOU) to jointly accelerate the market adoption of medium- and heavy-duty electric vehicles. To reduce diesel emissions and GHG emissions, the coalition seeks to ensure that 100 percent of all new medium- and heavy-duty vehicle sales be ZE by 2050, with a 2030 target of 30% ZE sales [234].

The signatories will work through the existing multi-state Zero-Emission Vehicle (ZEV) Task Force facilitated by the Northeast States for Coordinated Air Use Management (NESCAUM) to develop and implement an action plan by early 2021.Moreover, the National Zero-Emission Truck (ZET) Coalition—organized by CALSTART—is working on a five-year point-of-sale incentive program of over $2 billion at the federal level [234].

7.2.2.2.3 International

In 2019, the European Union adopted its first CO_2 standards for heavy-duty vehicles where the transport sector is responsible for almost a quarter of CO_2 emissions. Thein 2019 standards call for manufacturers to cutCO_2 emissions for new trucks on average by 15% in 2025 and 30% in 2030, compared to 2019 levels [235]. In response, truck manufacturers have called on the EU to invest in charging and refueling infrastructure, and to establish a set of consistent and predictable policy measures.

7.2.2.3 Reaching LC1 Targets

To reach the goals outlined in the Low Carbon 1 (LC1) trajectory, the next few years will be driven mostly by the Advanced Clean Trucks regulation. Current demonstration projects should be continued (such as those by Volvo at the SPBP or BYD at Port of Oakland) to identify potential problems with ZE technologies. They should also be extended to promising new ZE drayage trucks.

Existing loan programs should be reinforced to help early adopters of ZE drayage trucks, with more financial assistance especially for independent owner-operators, who have limited access to credit. One possibility is to beef up (and restrict to ZE trucks) CARB's Truck Loan Assistance Program, which was started in 2009 to help small business truck owners acquire cleaner trucks.

To limit the ports' financial risk, a pilot leasing program could be considered for a few years to build up the market for ZE drayage trucks, until it starts to become sustainable and technology has matured. The tax on containers instituted by the SPBP is a good initial source of revenue for vehicle incentives, but it is currently too low in the long term to replace a large percentage of conventional drayage trucks, so alternative sources of revenue will need to be identified. These sources could include port entry fees for conventional drayage trucks, that could increase over time, and that could be waived for zero-emission drayage trucks.

In addition to quantifying the health and environmental benefits of ZE heavy-duty trucks, local and regional studies are needed to identify their potential benefits on traffic, traffic safety, and infrastructure demand, especially if they are coupled with connected vehicle technologies.

As part of a portfolio of measures targeting the replacement of all conventional drayage trucks with ZE trucks, California ports may consider a ban on diesel drayage trucks by a specific date, an approach similar to the Clean Trucks Program at the SPBP, possibly coupled with a scrapping program. While drayage trucks are transitioning to ZE, existing emission regulations should be enforced as much as practically possible, including the ATCM on HDD diesel truck idling.

In the meantime, the ports should work with logistics firms, electric utilities, and the state to plan, finance, and start building a network of charging stations along major drayage routes in the state. In addition, the states should start working with community colleges and the California State University system to train the workforce needed to build and maintain both ZE drayage trucks and the related infrastructure.

Finally, we cannot overemphasize the importance of policy stability and predictability in bringing truck operators and logistics firms on board to adopt ZE technologies and to ensure a smooth transition to ZE heavy-duty trucks in port operations.

7.2.3 Long-haul Trucks

In this section, we consider long-haul trucks, where long-haul trucking involves driving 250 miles or more.

7.2.3.1 Long-haul Truck Projections and Characteristics

Projections for the number of long-haul trucks through 2045 are displayed in Figure 7.5 for both the Business as Usual (BAU) and Low Carbon (LC1) trajectories.

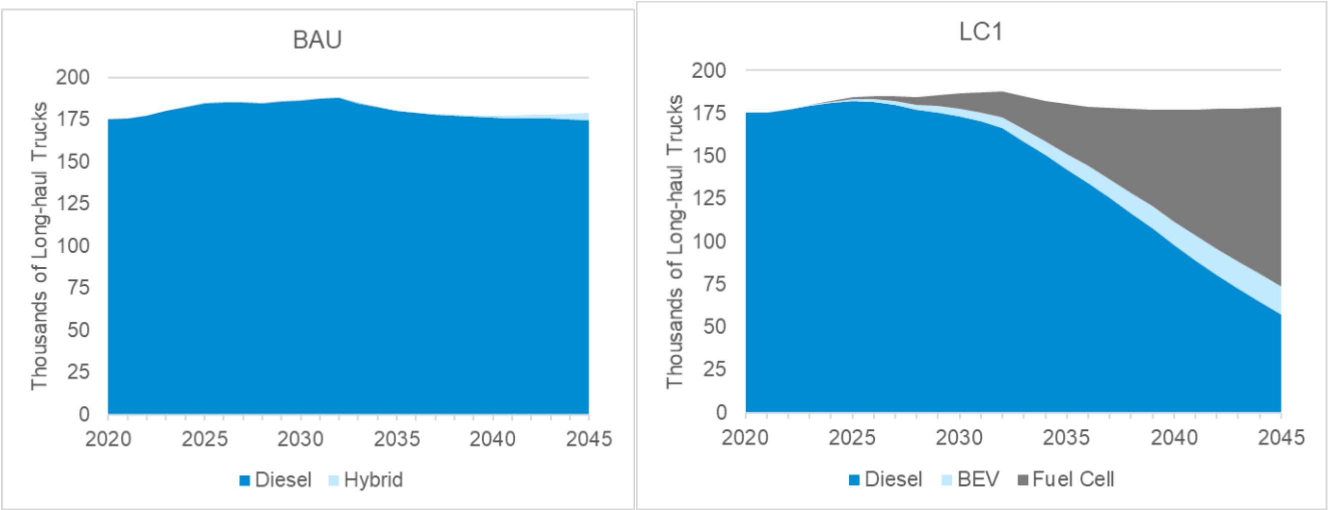

Figure 7.5. Long-haul truck fleet projections for BAU (*left*) and LC1 (*right*).

Note the high number (around 180,000) of long-haul trucks projected to be on the road. The BAU trajectory for long-haul trucks is nearly entirely composed of diesel internal combustion engine vehicles (ICEVs), with modest additions of diesel hybrid electric vehicles (HEVs) starting in the mid-2030s. The LC1 trajectory leads to a transition from ICEVs to zero-emission vehicles (ZEVs) including both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Compared to the BAU, LC1 transitions from ICEVs one decade sooner and results in a more complete reduction of ICEVs, with 68% being ZEVs by 2045 rather than 6.1% being HEVs. Long-haul trucks have high miles traveled compared to other HDVs (US Department of Energy, 2018). Therefore, fuel incentives could be particularly effective at reducing emissions of long-haul HDVs.

7.2.3.2 Technology Constraints for Long-haul Trucks

Long-haul trucks may be more challenging to transition to ZEVs compared to other vocations due to their significantly longer routes and less-frequent tendency to return to a depot, or “home base” location where charging/fueling infrastructure can be aggregated [236]. CARB estimates that approximately 60% of long-haul vehicles miles traveled (VMT) comes from out-of-state and international vehicles [237].

The lack of commercially available ZE trucks and the associated infrastructure are major barriers to ZEV adoption for long-haul applications. As of 2020, long-range electric vehicles are in the precommercial stage. Tesla has been accepting preorders for its Tesla Semi (300-mile and 500-mile range options) (Tesla, 2019) [238] and both Toyota and Nikola are planning to commercialize Class 8 fuel cell trucks with ranges between 300 and 750 miles within the next one to three years [239], [240]. Pilot programs (e.g., Volvo LIGHTS, etc.) are critical for the nascent state of long-haul ZEV technologies. These programs prove current capabilities, find issues with the current technology, and provide the testing needed for improving technology readiness by deploying limited numbers of vehicles in fleets [241]. Hybrid powertrains- are another option under development. They reduce diesel fuel use and, for plug-in hybrid variants, offer the use of electricity for a portion of their transportation fuel needs.

7.2.3.3 Long-haul Truck Policies

Policies affecting long-haul trucks are detailed in the following sections, separated by whether they apply to long-haul trucks or the fuels they use. Policies are further categorized by location: whether the programs are administered by the state of California, the United States, or elsewhere.

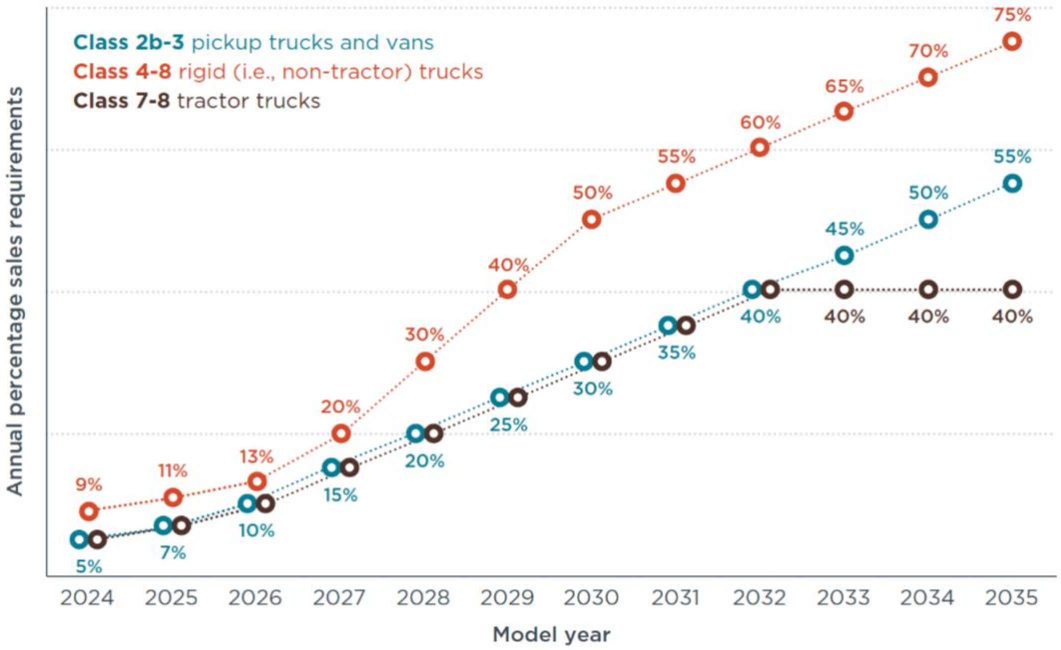

Figure 7.6. Zero-Emissions Sales Schedule by Vehicle Category under California's Advanced Clean Trucks regulation. Source: from International Council on Clean Transportation (ICCT), n.d. [242]

7.2.3.3.1 California

A number of policies and incentives mentioned above apply to long-haul vehicles. The California Statewide Truck and Bus Rule, which was initially adopted by CARB in December 2008, requires all heavy-duty diesel trucks and buses operating in California with a GVWR over 14,000 pounds to have their engines retrofitted or replaced in order to reduce their emissions of PM, NO_x, and other pollutants. To comply with this regulation, fleet owners have three options: 1) Implement the Best Available Control Technology (BACT) based on a compliance schedule for engine model year starting in 2011; 2) A percentage of their fleet must meet PM BACT by January 1 of each compliance year by retrofitting or replacing the engines of their HD diesel vehicles; or 3) Their fleet must meet an average requirement set by CARB for PM and NO_x. A number of vehicles are exempt from the Truck and Bus Rule including (this list is not exhaustive) drayage trucks, vehicle used for solid waste collection, and vehicles subject to the fleet rule for transit agencies.

For GHG emissions, the main regulations are Phase 1 and 2 GHG standards. The major driver for long-haul electrification is the newly adopted Advanced Clean Trucks regulation, which mandates that 40% of sales for class 8 tractors within the state are ZEZE options by 2035 [243]. See Figure 7.6 for the full schedule. We note, however, that the purchase of ZE long-haul trucks can be subsidized via the funding programs for ZE medium- and heavy-duty trucks mentioned above (HVIP, Carl Moyer Program, VW, or the Truck Loan Assistance Program), although these programs have limited financial resources, and they are providing incentives for other truck categories.

Following the Governor's Executive Order N-79-20 (issued on September 23, 2020), which sets a goal of 100 percent of ZE medium- and heavy-duty vehicles in the state by 2045 where feasible, CARB has been developing a medium- and heavy-duty ZE fleet regulation (“Advanced Clean Fleet”) with the goal of meeting the target set by EO N-79-20. The initial focus would be on larger fleets with vehicles that are suitable for early electrification [23].

7.2.3.3.2 United States

California is also engaged in multi-state initiatives, such as the Multi-State Medium- and Heavy-Duty Zero Emission Vehicles Memorandum of Understanding (MHD ZEV MOU) signed on July 14,2020 [244]. The MOU committed 15 states to work together to grow and accelerate the market for electric medium- and heavy-duty (MHD) vehicles. MHD vehicles include large pick-up trucks, vans, delivery trucks, box trucks, school and transit buses, as well as long-haul delivery trucks. In addition to California, the states that signed the MOU are Connecticut, Colorado, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington. The goal of the signatories is that all new MHD sales will be ZE by 2050, with an intermediate target of 30 percent MHD ZE sales by 2030. The signatories are working through the multi-state ZEV Task Force facilitated by the Northeast States for Coordinated Air Use Management (NESCAUM) to develop and implement an action plan by early 2021 (within six months of the date when the MOU was signed).

7.2.3.3.3 International

Euro VI emissions regulations were put into effect in 2013 and 2014. They are similar to US 2010 standards in that they provide limits on emissions over several years and set distances traveled. EU Member States can offer tax incentives to buyers to go toward or totally cover the additional cost of complying with the limits ahead of schedule, whether that involves retrofitting or scrapping a vehicle [245]. In Japan, the Post New Long-Term Emissions Standards fully went into effect in 2010 and are similar to both US 2010 and Euro VI standards in scope and approach by limiting emissions of HDVs [246]. China VI emissions regulations are being implemented in two phases: (1) VI-a is similar in standards to the Euro VI emissions regulations and (2) VI-b includes tighter testing regulation and remote monitoring of emissions [247].

7.2.3.4 Reaching LC1 Targets

The relative simplicity of the HVIP and Low NO_x Engine Incentives programs administered through registered dealers encourages fleet owners of any size fleet to pursue incentives for vehicle replacement. These types of voucher programs should therefore be emulated for their clarity, ease of use, and alignment of incentives between fleet owners, registered dealers, and regulatory agencies.

A combined “carrot and stick” approach is likely to be more effective than a single “carrot” or “stick” policy. The HVIP and Low NO_x Engine Incentives provide “carrots” to encourage the uptake of ZE trucks. Aligned “stick” policies, such as differentiated impact fees for long-haul trucks based on standards compliance, would encourage more aggressive purchasing of compliant trucks, while also raising additional revenue which could be used to reward ZEVs with a rebate.

7.2.4 Truck Classes 2b and 3

7.2.4.1 General Characteristics

Truck Classes 2b and 3 represent vehicles with a GVWR of 8,500–10,000 lbs. and 10,000–14,000 lbs., respectively. These vehicles have a wide range of commercial applications. They include pickup trucks and van bodies like personal vehicles in Classes 1 and 2a, but these vehicles have a higher GVWR to meet different functional requirements as they are mostly used for commercial purposes.

In California, there are approximately one million registered Class 2b and 3 vehicles. Approximately 43% run on gasoline and 57%on diesel [248]. The annual sales of Class 2b and 3 vehicles in California are 75,000 and 54,000, respectively [249].

Data from the Vision 2.1 model [197] indicate that Class 2b and 3 vehicles account for 20% of NO_x emissions, 26% of $PM_{2.5}$ and PM_{10} emissions, and 17% of CO_2 emissions of all heavy-duty vehicles (Class 2b–8). Pre-COVID-19 estimates of Class 2b and 3 vehicle emissions for year 2020 are shown in Table 7.3. 2020 [224].

The duty cycles of Class 2b and 3 trucks vary across industries and purposes. Some businesses, such as plumbers and landscapers, use their fleets for short trips while others, such as shuttle operators, use them for longer trips. Some fleets, such as delivery trucks, are used mostly for tour operation with multiple daily stops, while other trucks are used for single trips (e.g., municipal trucks). Other differences include time of day and duration of operation and whether trucks return to their base.

Table 7.3. 2020 Air pollutant emissions for Class 2b and 3 vehicles in California (ton/year)

	NOx	PM10	PM2.5	CO2e
Class 2b-gas	4,485	177	76	2,773,758
Class 3-gas	625	39	16	690,651
Class 2b-diesel	14,602	597	326	1,702,795
Class 3-diesel	3,235	231	116	986,934
Total	22,947	1,044	534	6,154,137

There are currently limited data and models available that effectively capture trip activity characteristics of Class 2b and 3 vehicles. Classification data are available statewide along major corridors from automated vehicle classification and weigh-in-motion sites. Light-duty commercial vehicles representing Classes 2b and 3 are also modeled in CSF2TDM.However, Class 2b and 3 vehicles cannot unambiguously be distinguished from passenger vehicles due to their similar axle configurations: they both possess two axles with similar and overlapping wheelbase characteristics. Hence, currently available data for Class 2b and 3 vehicle counts do not reliably reflect their activity. In addition, available truck GPS data sources skew significantly towards heavy-duty truck fleets and are not a good source for capturing light-duty truck trip characteristics. Also, unlike heavy-duty trucks (especially tractor trailers) which are mainly associated with freight movement, most light-duty trucks perform vocational functions with a minority involved in freight movements captured by the Commodity Flow Survey, after which the freight component of CSF2TDM is modeled. These data limitations have impacted CSF2TDM's current ability to provide reliable overall estimates of light-duty truck activity.

Recent research has shown the potential of using advanced technologies such as stationary Light Distance and Ranging (LiDAR) sensors to obtain and reconstruct detailed three-dimensional profiles of vehicles from roadside installations [250]. Advanced vehicle classification models developed from this research demonstrate the ability to provide detailed characterization of trucks and have the potential to be expanded to effectively distinguish light commercial trucks from passenger vehicles and better infer their vocational and freight affiliations, thus addressing limitations of current traffic monitoring systems.

7.2.4.2 Current Policies

Phase 1 and 2 GHG standards apply to Class 2b-3 vehicles. Several programs currently offer incentives for owners or potential owners of Class 2b and 3 vehicles to switch to a ZEV.

7.2.4.2.1 California

In California, the HVIP helps fund the purchase of ZE and plug-in hybrid trucks and buses, including Class 2b-3 vehicles, vehicles that use engines that meet the optional low-NO_x standard, and trucks equipped with electric power takeoff systems. Class 2–8 s HVIP is a first-come, first-served voucher program. It provides higher incentive amounts for fleets domiciled in disadvantaged communities. Incentives for Class 2b and 3 trucks range from $25,000 to $60,000 per vehicle based on weight class and whether the truck is located in a disadvantaged community [248].

7.2.4.2.2 United States

Two other incentive programs could be analyzed to learn from the accumulated experience. The first is the New York Truck Voucher Incentive Program, which is aimed at accelerating the deployment of all-electric and alternative fuel trucks and buses in medium- and heavy-duty vehicle classes throughout New York State by reducing their upfront purchase costs and payback period. It covers Class 3–8 [251]. The first round of the program, active from 2013 through mid-2018, provided about $14 million for 60 fleets and 594 vehicles. The next round has been active since then. It has a funding cap of $60,000 per vehicle for Class 3C [252].

The second program is Drive Clean Chicago, which was active between 2014 and 2017 and was created to help Chicago fleet owners purchase cleaner vehicles. Funded by the federal Congestion Mitigation Air Quality (CMAQ) program, Drive Clean Chicago provided approximately about $11 million to help deploy more than 288 Class 2–8 trucks and buses that are cleaner than comparable conventional diesel vehicles [253]. There is no information about how many Class 2b and 3 vehicles were deployed by the program.

7.2.4.2.3 International

The Chinese government identified 13 cities to pilot electric public transport in 2009. It provides subsidies while each city develops its customized implementation plan. The program now is a large-scale program that includes more cities and more vehicles (more than 88 cities by 2016, He et al. 2013). Furthermore, each city has autonomy to choose vehicle types, including cars, taxis, buses, sanitation trucks, delivery vehicles and trucks, and to make other specifications. Funds for these programs come from China's central government and from local government sources which sometimes match the central government amount [254]. Incentives are in forms of direct purchase subsidies, reduced tolls on roads, reduced vehicle licensing fees, and bulk purchase incentives [255].

7.2.4.3 Reaching LC1 Targets

A variety of policies and incentives could be considered to foster the adoption of ZEVs within Classes 2b and 3, including loans to independent and small fleet owners, coupled with lease programs to accustom prospective owners with ZE technology. To complement these incentives, which are designed to encourage early adoption of ZE technologies, additional regulations could be put in place to accelerate the adoption of commercially available technologies. For example, Phase 2 GHG standards could be tightened and gas prices progressively increased to further accelerate the adoption of ZE Class 2b-3 vehicles.

As for other truck classes, because plug-in hybrid electric vehicles (PHEVs) have a longer range than BEVs, they would be more suitable for fleets with varied or uncertain trip length and possibly many stops, while BEVs would be more suitable for fleets with shorter and fixed-range trips due to their still relatively limited battery size. For example Birky et al. (2017) [256] recommended promoting PHEVs and BEVs for the following business categories:

PHEV

- Utilities and telecommunication firms;
- Service providers such as landscapers, plumbers, electricians, and contractors;
- Emergency responders such as ambulances, police, traffic control flaggers; and
- Catering.

BEV

- Local/regional parcel delivery;
- Local/regional grocery delivery;
- Ridesharing, where vehicles drive about 30–50 miles one way;
- Passenger shuttles for churches, hotels, airports, and hospitals; and
- Military, government, or educational campus fleets.

To accommodate vehicle heterogeneity, advances in modular and scalable battery packs for BEVs would allow businesses to customize their vehicle to their range and duty cycle requirements [256]. Relevant trip characteristics include trip length frequency, number of stops, and charging/fueling station availability during operation.

7.2.5 Construction Equipment

7.2.5.1 General Characteristics

Construction equipment us a major source of air pollution, which is especially of concerns for construction sites close to inhabited areas, particularly in urban areas.

Construction equipment may operate on or off road. On-road vehicles are mostly dump trucks and concrete mixers, while examples of off-road vehicles include bulldozers, loaders, backhoes, graders, excavators, trenchers, compactors, and cranes. The number of off-road construction and mining equipment vehicles is projected to be around 142,000 in California by 2020, according to the CARB Vision 2.0 off-road model [257].

Policies and incentive programs are typically different for these two categories of vehicles/equipment. Off-road construction vehicles are often grouped with other off-road equipment such as agricultural machinery, while on-road construction vehicles are grouped with other categories of heavy-duty trucks.

The CARB Vision 2.0 model estimates off-road construction and mining equipment emissions for the 2020 target year as shown in Table 7.4. 2020 [257].

Table 7.4. 2020 Off-road construction and mining equipment emissions

	NO_x (tons/year)	$PM_{2.5}$ (tons/year)	CO_2 (tons/year)
Construction and mining equipment	18,396	766.5	19,900,000

Source: Vision 2.1

Off-road construction and mining equipment accounts for 67% of total NOx emissions of all off-road equipment in the off-road module of Vision 2.0 (which includes airport ground support equipment, industrial equipment, oil drilling and construction and mining equipment), 78% of $PM_{2.5}$, and 60% ofCO_2.

We used the Vision 2.1 model [197, p. 1] to estimate on-road construction vehicle emissions for the 2020 target year as shown in Table 7.5. 2020. The inventory of construction vehicles in this model is obtained as a percentage from each group (Classes 6, 7 and 8 in-state and California International Registration Plan (CAIRP)) based on economic indicators; these estimates are not based on the Department of Motor Vehicles or the IRP database.

Table 7.5. 2020 On-road construction trucks emissions

	NOx (tons/year)	PM_{10} (tons/year)	$PM_{2.5}$ (tons/year)	CO_2 (tons/year)
Class 6 In-state Construction Small	1,250	102	55	581,627
Class 7 In-state Construction Heavy	425	30	14	214,064
Class 8 CAIRP Construction	599	17	8	217,179
Class 8 Single Construction	1,200	42	18	547,925
Class 8 Tractor Construction	1,163	33	16	411,173
Total	4,637	224	110	1,971,969

Source: Vision 2.1

These on-road construction vehicles account for 4% of total NOx emissions for all on-road heavy-duty vehicles (Class 2b-8), 6% of PM_{10}, 5% of $PM_{2.5}$ and 5% ofCO_2 on 2020.

7.2.5.2 Selected Policies for ZE Construction Vehicles/Equipment

On-road construction vehicles are subject to the Truck and Bus Regulation. However, low mileage construction trucks owned by a contractor who has a valid license issued by the California Contractors State License Board and certain truck body types regardless of who owns them (concrete mixers, concrete pump trucks, water trucks, and tractors used exclusively to pull low-boy trailers) were allowed to defer compliance if they met some eligibility criteria. However, vehicles with a GVWR greater than 26,000 lbs using this option will need to be replaced per the engine model year schedule beginning January 1, 2020 [258].

Off-road vehicles and equipment are subject to the California in-use off-road diesel-fueled fleets regulation, which was adopted in 2007. Its goal is to reduce PM and NO_x emissions from in-use (existing) off-road heavy-duty diesel vehicles in California by requiring by the installation of diesel soot filters and encouraging the replacement of older, dirtier diesel engines with newer, cleaner ones. The regulation covers a wide scope of vehicle types used in a broad range of industries, including construction (but also air travel, manufacturing, landscaping, and ski resorts). II applies to most two-engine vehicles (except on-road two-engine sweepers) and to all self-propelled off-road diesel vehicles with a 25 hp or greater engine. It includes vehicles that are rented or leased [259], [260].

Our exploration of US programs targeting off-road construction vehicles/equipment yielded only one additional result: the New Jersey Clean Construction program. This program funded by the U.S. EPA and administered by the N.J. Department of Environmental Protection. Created, began in 2009, its goal is to reduce air pollutant emissions off-road vehicles by installing tailpipe retrofit equipment on the following types of construction equipment:

- Construction equipment used on projects conducted in urban/sensitive areas;
- Construction equipment with the highest use; and
- Older construction equipment.

7.2.5.3 Incentives

Though there are few if any incentive programs exclusively targeted at on-road construction vehicles in California, the eligibility requirements for several general California vehicle incentive programs are broad enough to apply to construction vehicles.

The Moyer Program provides grants to cover the incremental cost of cleaner-than-required engines, equipment, and other technology, including for on-road construction vehicles and off-road construction equipment via the state reserve of the Carl Moyer Program, which has funds set aside for specific project types. To qualify, emission reductions should be permanent, surplus, quantifiable, enforceable, and creditable to the State Implementation Plan (SIP). Covered pollutants include NO_x, reactive organic gases (ROG), and PM.

Another source of funding is the Clean Off-Road Equipment Voucher Incentive Project (CORE), a new $44 million program, whose purpose is to encourage California freight equipment users to lease or purchase zero-emission off-road freight equipment. This streamlined voucher incentive program helps offset the higher cost of zero-emission technology with a point-of-sale discount. There is no scrappage requirement. Additional funding is available for charging and fueling infrastructure and for equipment deployed in disadvantaged communities. As of August 2020, however, CORE no longer accepted voucher requests because budgeted funds had been spent [261].

We should also mention the Off-Road Replacement Program administered by the San Joaquin Valley Air Pollution Control District in California. This program provides incentives to replace heavy-duty off-road mobile equipment used in construction and other non-agricultural services.

In addition, the heavy-duty ZEV Replacement Grant by South Coast Air Quality Management District (SCAQMD) offers funds for replacing Class 8 HDVs with ZEVs. Funds cover up to 75% of non-government project costs, 100% of government project costs and up to $2,700,000 total. Eligible class 8 construction vehicles include dump trucks, and concrete mixers. This program is funded by California's portion of the Volkswagen Environmental Mitigation Trust [262].

We are not aware of any previous study of the effectiveness of programs and policies in place for construction vehicles. However, CARB's Low Carbon Transportation Investments and Air Quality Improvement Program includes provisions to analyze the effectiveness of its policies and incentive programs. Results from the analysis of this program are expected by summer 2022.

7.2.5.4 Reaching LC1 Targets

Although on-road construction vehicles, mostly travel locally and stay close to their home base. For example, dump trucks usually operate within a facility like a construction site or between a job site and a (dirt or gravel) dump station. They often do not return to base until the end of their shift. On the other hand, construction equipment such as concrete pump trucks and cranes travel to a job site and operate there for periods ranging from a few hours to a few days before returning to base. Different policies and strategies should be considered to account for the heterogeneity of travel patterns and operations among construction vehicles/equipment. For equipment with tour-based behavior, FCEVs may be a good fit as refueling time is short (compared to BEVs) and those vehicles could refuel easily during their shift. Limitations associated with FCEV include high cost of fuel and availability of refueling infrastructure. Conversely, BEV technologies may be more attractive in urban areas where a connection to local electrical infrastructure is possible for equipment that stays at a job site.

7.3 Charging/Refueling Infrastructure

7.3.1 General Considerations

Charging and refueling stations for medium- and heavy-duty BEVs and FCEVs may be designed to support 1) an individual fleet without public access; 2) a group of fleets with an agreement to share access; 3) public access for all medium- and heavy-duty vehicles; or 4) public access for all vehicle types.

Fleet-specific infrastructure (Option 1) is more likely to be located at depot facilities (i.e., "home base" locations), to ensure ready access during breaks and end-of-shift dwell periods. Examples of current projects using this approach are Tesla's fast charging stations installed at Anheuser-Busch and United Parcel Service facilities [263].

Stations shared by a select group of fleets (Option 2) may be installed at a shared operating location or offsite along common routes. Examples are ZEZE drayage truck projects at the Port of Long Beach and Port of Los Angeles: BEVs will be able to charge at fleet facilities at the ports and FCEVs will be able to refuel at the ports as well as along routes [231], [264], [265].

Fully public stations (Option 3) may be located along commonly traveled roadways, such as major freight corridors to maximize access. So far, hydrogen refueling station construction has tended to be on a fleet-by-fleet basis due to low FCEV truck volumes and high capital costs; however, as BEV and FCEV adoption grows in the medium- and heavy-duty sectors, the other station business models may become more prevalent.

In the case of hydrogen refueling stations, Option 4 would most likely be a station primarily for medium- and heavy-duty vehicles with a separate dispenser for light-duty vehicles (e.g., a truck stop). Several constraints may limit heavy-duty vehicle use of light-duty vehicle-based infrastructure. For example, currently heavy-duty vehicles tend to store hydrogen at different pressures. They may have too large an electricity or hydrogen demand for a light-duty station’s established capacity. Medium- and heavy-duty vehicles have different fueling protocols than light-duty vehicles [266] (although this may be addressable via software changes), and vehicles may not be able to physically navigate the light-duty vehicle station due to station location, vehicle size, and turning radius. Class 2b and 3 vehicles are more likely to be able to rely on light-duty ZE infrastructure due to their size and mixed purpose as personal and commercial vehicles [256], [267].

7.3.2 Hydrogen Infrastructure Requirements

In 2013, California Assembly Bill 8 authorized funding for 100 public hydrogen fueling stations through the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) [268]. In 2018, Executive Order B-48-18 set a goal of 200 hydrogen stations by 2025. Neither of these directives specified how many stations should serves light-duty versus medium- and heavy-duty vehicles. The California Fuel Cell Partnership (CaFCP), a government/industry collaborative, also released its vision for 1,000 hydrogen refueling stations by 2030 [269]. This plan would include stations for all vehicle types.

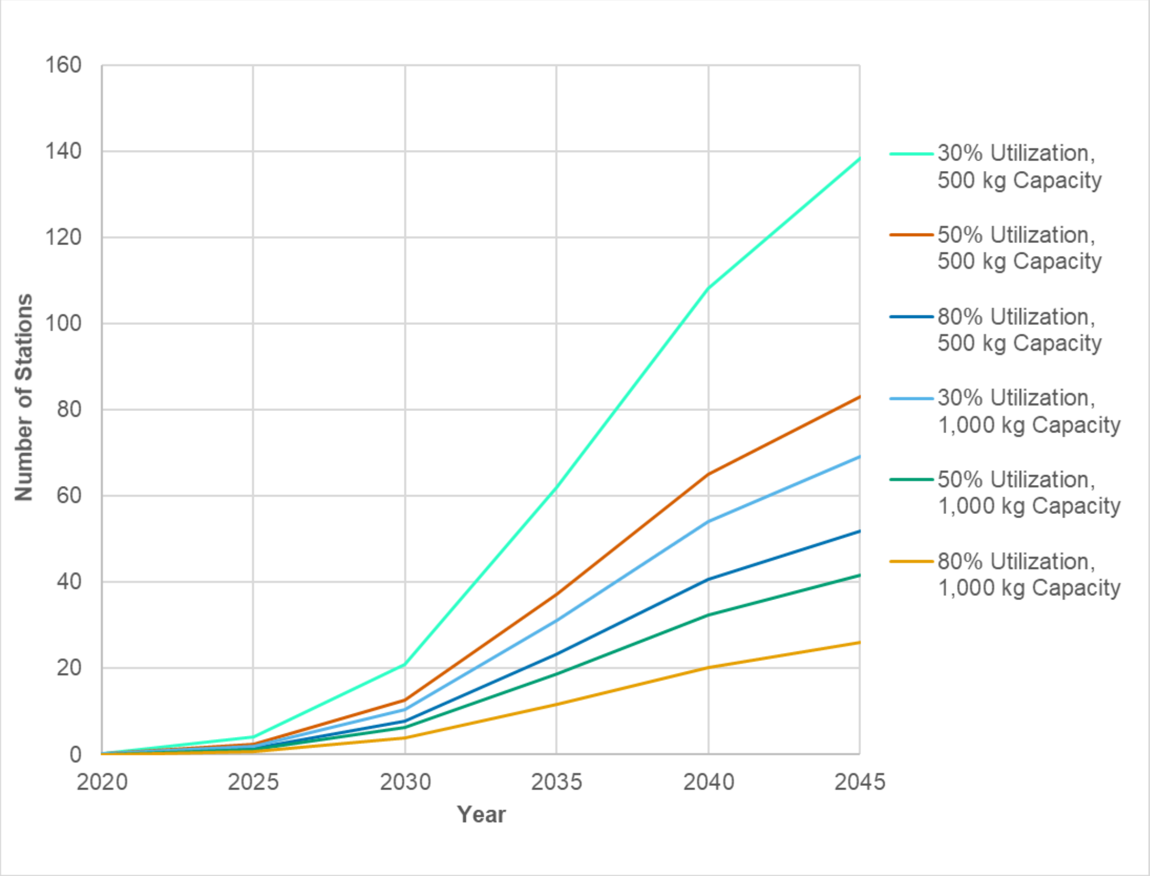

Figure 7.7. BAU Medium- and Heavy-Duty Vehicle Hydrogen Refueling Stations year 2020–2050 (500 and 1,000 kg Station Capacities): Class 4–8

Figure 7.7, Figure 7.8, and Figure 7.9 show the number of stations assuming the business-as-usual (BAU) and Low Carbon (LC1) trajectories, respectively, for different station capacities and daily utilization levels (% station capacity) assuming public access across medium- and heavy-duty fleets. Station capacity refers to the amount of hydrogen at the station that can be dispensed in a day. Higher utilization would result in more frequent hydrogen production/delivery. In these figures, Class 2b and 3 vehicles are separated from Class 4–8 vehicles due to their likely different station requirements, including station siting, fueling protocols, and fueling pressures, due to vehicle characteristics and vehicle spatial and temporal travel patterns. In the future, Class 2b and 3 vehicles may rely on a mix of light-duty and fleet-based charging and hydrogen fueling infrastructure [256].

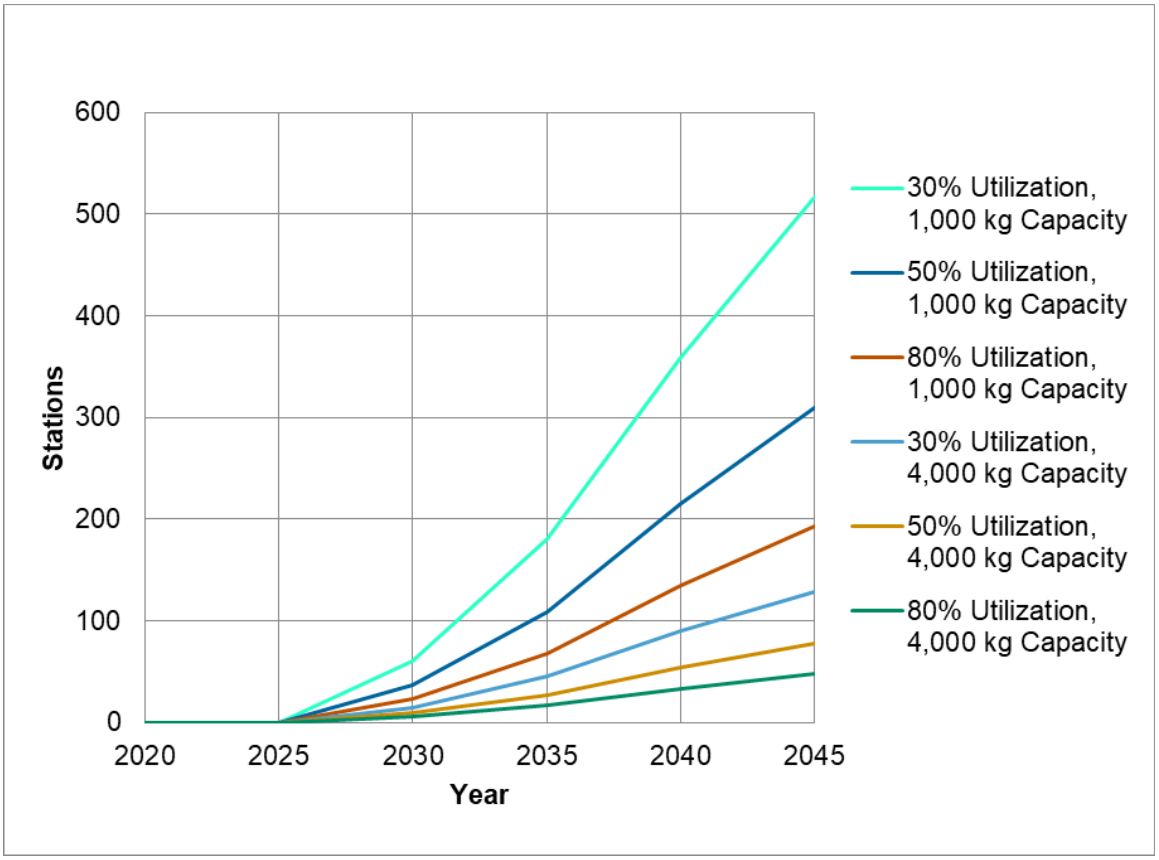

Figure 7.8. LC1 Medium- and Heavy-Duty Vehicle Hydrogen Refueling Stations for Class 2–b–3

For the BAU trajectory, the average station capacity is assumed to be either 500 or 1,000 kg; the latter is at the high end of current hydrogen station development. The BAU trajectory does not have any FCEVs for Classes 2b and 3, so Figure 7.7 represents only Class 4–8 supply. For the LC1 trajectory, we considered station capacities of 1,000 and 4,000 kg. The higher value reflects higher overall demand for hydrogen. In reality, some stations will experience higher or lower utilization depending on proximity to truck traffic. In addition, stations may be sized differently depending on location and current/future demand expectations. In addition, these results are based on bulk hydrogen needs and do not take into account the spatial distribution of hydrogen demand across the state. Spatial accounting of demand may increase the number of stations and reduce average station utilization if the demand is more dispersed.

Under the BAU trajectory, station growth is relatively low and significantly under the current state targets. As can be seen in Figure 7.7, the number of stations needed increases with lower average station utilization. Station capacity can also have a significant impact on the total number of stations needed, as smaller stations will result in fewer vehicles served per station at a given utilization.

Under the LC1 trajectory, demand for hydrogen is significantly higher compared to the BAU trajectory, which reflects the high ZEV adoption required to meet the goal of carbon neutrality by 2045. Examining the station capacity in years 2025–2035, statewide station numbers are within the range supported by the current executive order and CaFCP vision. Due to the greater demand for hydrogen, the total number of stations spans a larger range under different station configuration assumptions.

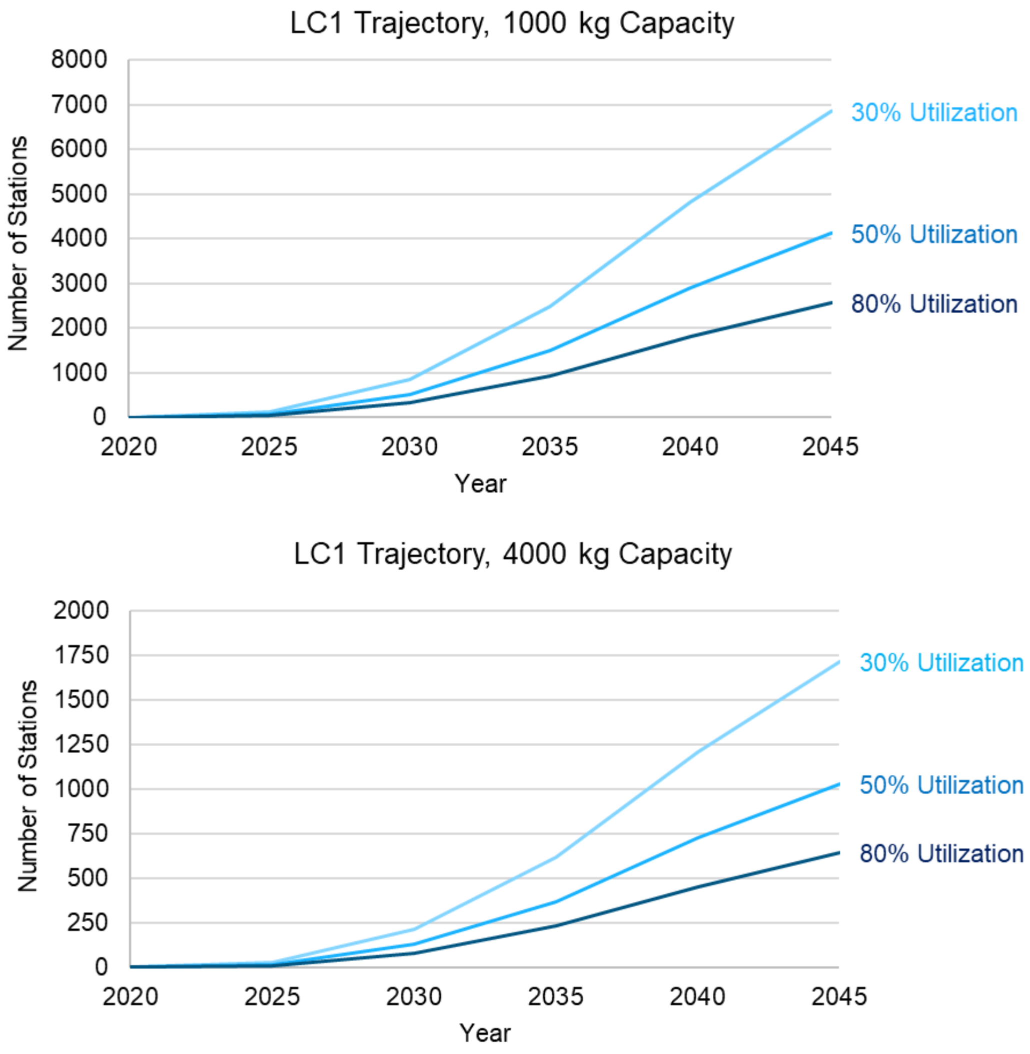

Figure 7.9. C1 Medium- and Heavy-Duty Vehicle Hydrogen Refueling Stations for Class 4–8. Top panel: 1,000 kg Station Capacity; bottom panel: 4,000 kg Station Capacity

7.3.3 Battery Electric Infrastructure Requirements

Under Executive Order B-48-18, the same order that directed agencies to prepare for 200 hydrogen stations by 2025, agencies were directed to work towards 250,000 electric vehicle chargers, including 10,000 DC fast chargers, also by 2025 [270]. Moreover, Assembly Bill 2127 (passed in 2018) required a statewide assessment of the charging infrastructure needed to support 5 million ZEVs by 2030 [271]. This analysis focuses on the electric vehicle supply equipment (EVSE) needs for medium- and heavy-duty vehicles between 2020 and 2045 under the BAU and LC1 trajectories.

Currently, there is limited information on what the optimal charger-to-vehicle ratio and ratio of charging rate capacities will be for medium- and heavy-duty vehicles. An ongoing project at Lawrence Berkeley National Laboratory funded by the California Energy Commission is developing a medium- and heavy-duty electric vehicle (Class 4–8) infrastructure projections tool (HEVI-Pro) (CEC 600-19-005). Preliminary results from this model show that a combination of 50-kW chargers at home base locations and 350-kW chargers at public locations results in a ratio of 1:1.7 for a 2030 deployment case, with 86% of chargers of size 50 kW [272]. Note that this tool does not include Class 2bCb and 3 trucks. More clarity is needed on whether a single EVSE unit is expected to provide support for more than one EVSE plug. Much of the capital cost is associated with the EVSE unit installation, so a multi-plug port could reduce costs per plug. The International Council on Clean Transportation assumes for its preliminary analyses that 44.4% of medium- and heavy-duty chargers will be 50 kW, 44.4% will be 150 kW, and 11.2% will be 350 kW [273].

Figure 7.10 and Figure 7.11 show the number of chargers to support medium- and heavy-duty vehicles under the BAU and LC1 trajectories, calculated based on different ratios of chargers-to-vehicles: 1:1, 1:2, and 1:5. The 1:1 case assumes that charging is available at most home bases or depots and some public locations (e.g., truck stops), similar to the current LDV approach. The 1:2 case corresponds to primarily home base charging, where chargers can support a combination of daytime and overnight charging, such that vehicles do not need to be rotated to ensure all vehicles are charged for the next shift. Finally, the 1:5 case corresponds to high-power fast charging (on the scale of 350 kW), where vehicles charge on a rotating basis.

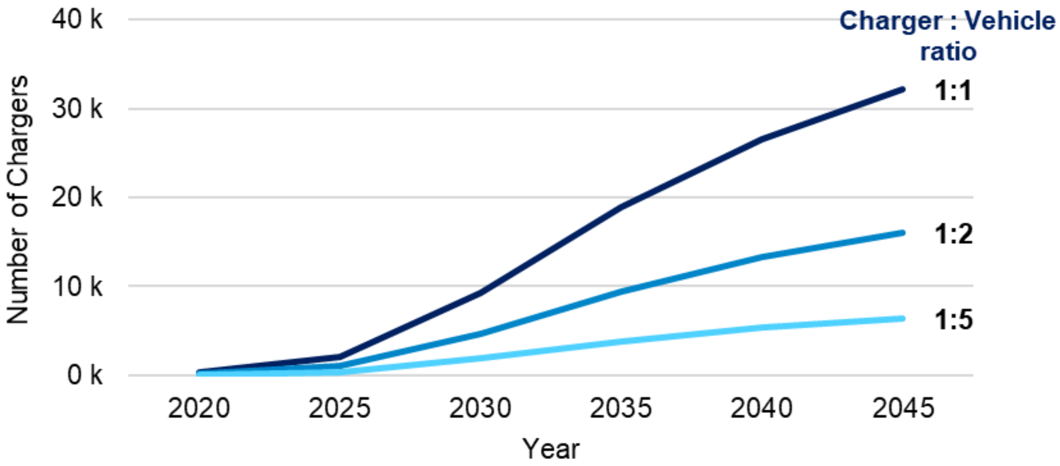

Figure 7.10. BAU Medium- and Heavy-Duty Vehicle Chargers for Different Charger-to-Vehicle Ratios

For the 1:1 case, Class 4–8 vehicles may rely on a combination of lower-power fast chargers (e.g., 25–120 kW) at home base and higher-power fast chargers (e.g., 200–350 kW) at public stations. The 1:2 case assumes that Class 4–8 vehicles charge at home base with a distribution of different charging rates, in line with the ICCT estimates (44.4% @ 50 kW, 44.4% @ 150 kW, 11.2% @ 350 kW), with the higher charging rates associated with fleets with larger gross vehicle weights and greater daily vehicle miles traveled VMT. The 1:5 case assumes that Class 4–8 vehicles have access to fast chargers on the scale of 200–350 kW, allowing for reduced charging times per vehicle and the possibility of using one charger for multiple vehicles.

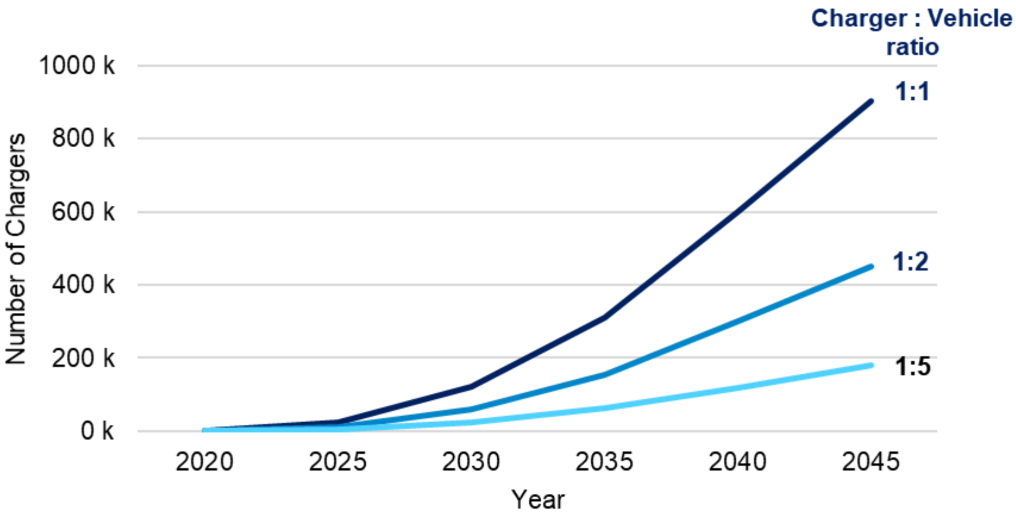

Figure 7.11. LC1 Medium- and Heavy-Duty Vehicle Chargers for Different Charger-to-Vehicle Ratios

Overall, the number of chargers needed to support a fleet will depend on performance needs weighed against budget considerations. High charging rates may reduce the total number of chargers needed per vehicles, but may introduce management challenges, such as vehicle rotation. If a fleet expects to charge overnight, rotating vehicles may not be feasible.

It is very unlikely that medium- and heavy-duty vehicles will use level 1 charging, and level 2 charging only makes sense for smaller medium-duty vehicles, specifically Classes 2bCesb and 3, or vehicles traveling over short distances and/or with long dwell times between uses. That being said, Class 2bCb and 3 vehicles make up a large percentage of medium-duty vehicles, and therefore, it may be reasonable to assume that a significant number of level 2 EVSE will be installed to support these vehicles.

Figure 7.12 and Figure 7.13 present the distribution of level 2 and DC fast chargers, assuming Class 2b and 3 vehicles rely on exclusively level 2 charging and Classes C4–8 rely on DC fast chargers of varying power ratings. Classes 2b and 3 are unique vehicle categories, as these vehicles may rely on a combination of public light-duty charging infrastructure, fleet-specific infrastructure, and public medium- and heavy-duty vehicle charging infrastructure (depending on the interoperability of chargers across vehicle types). If Class 2b and 3 vehicles are assumed to use DC fast charging, the total number of DC fast chargers would increase significantly, as would the cost of the charging network. Most likely, the type and power rating of chargers installed among fleets will vary depending on the types of vehicles within the fleet (e.g., transit buses versus delivery vans) and other specific fleet needs. Due to the higher cost of DC fast chargers compared to level 2 chargers, there may be a mix of both kinds serving medium- and heavy-duty vehicles. The Argonne National Laboratory estimates level 2 chargers cost between $5,000 and $9,000 per charger and DC fast charging stations are close to $60,000 per charger [274]. The ratio of chargers to vehicles may vary by fleet, due to differences in vehicle duty cycles and economic considerations, with the overall charger-to-vehicle ratio for the state unclear at this time.

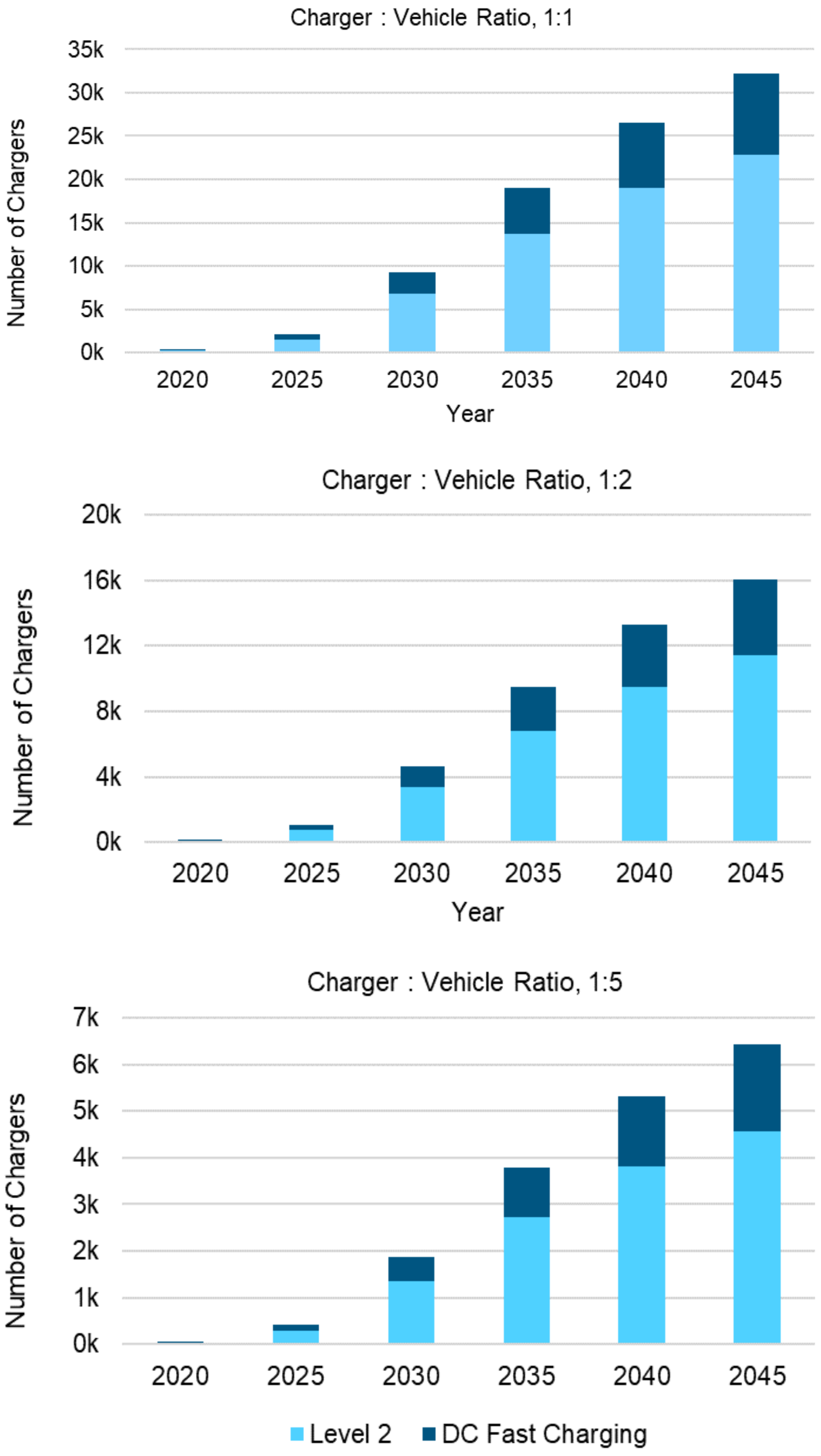

Figure 7.12. Distribution of Level 2 and DC Fast Charging for BAU Trajectory with different charger:vehicle ratios.

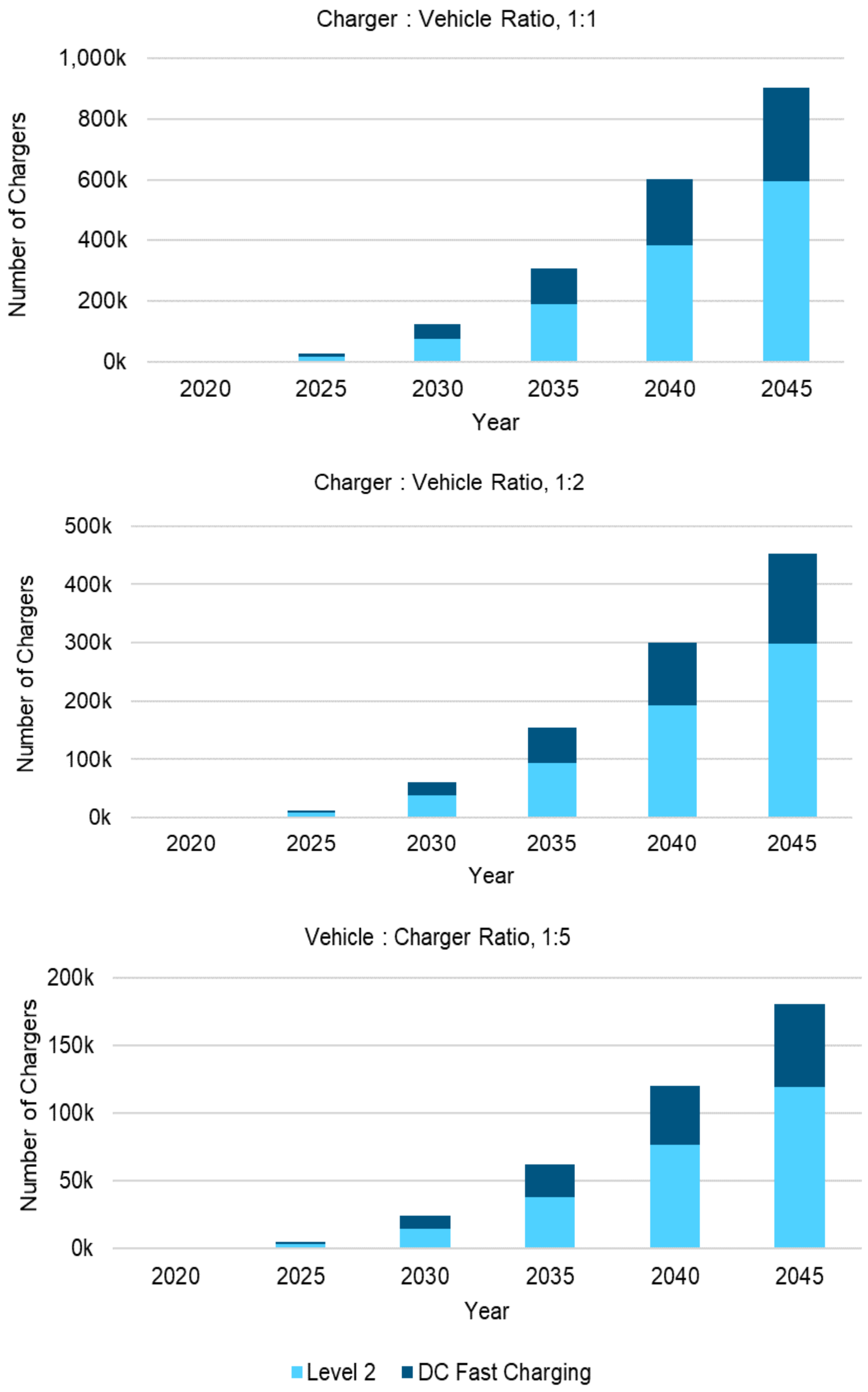

Figure 7.13. Distribution of Level 2 and DC Fast Charging for LC1 Trajectory

Whether DC fast charging stations will serve a combination of light-, medium-, and heavy-duty vehicles will depend in part on the interoperability of chargers to support these different vehicles as well as station design (e.g., accommodating greater vehicle height, turning radius). In addition, medium- and heavy-duty vehicles will need to charge for longer periods of time, which can affect station throughput and peak power demands at a station. In response to Senate Bill 1000 [275] [276], there is a five-year demand charge holiday for commercial vehicle charging by major utilities in California, although time-of-use utility pricing may still drive up costs if vehicles charge during peak times [277]. A fleet may weigh capital costs versus fuel costs to determine if installing more chargers would result in lower long-term costs, assuming more chargers could help the fleet capitalize on using electricity during off-peak, low-cost times of the day.

7.4 Overall Recommendations to Reach LC1 Targets

Given the economic importance of trucks to the economy of the state, it is critical to try to consult with all stakeholders when considering policies that will replace conventional medium- and heavy-duty vehicles with zero-emissions equivalents. Our main recommendations can be summarized as follows.

1. ZE heavy-duty vehicle technologies are essential to fully decarbonize the transport sector and meet California's climate goals. Indeed, heavy-duty trucks contribute disproportionately to air pollution, which disproportionately impacts disadvantaged communities and communities of color, and heavy-duty truck activity keeps growing.
2. Aggressive near-term action to promote ZE trucks makes sense. As shown in a recently concluded CARB HDV project (16RD011), pursuing ZE trucks more aggressively in the near term could result in important cost reductions that will benefit long-term deployment by speeding up learning.
3. Depending on the pace of electrification, new GHG standards (Phase 3) will likely be needed in partnership between the federal government and California. As much as possible, they should be uniform across the country to minimize the regulatory burden on manufacturers and truck operators, and to increase the chances of buy-in from all parties involved.
4. Quantify, demonstrate, and communicate benefits of ZE medium- and heavy-duty trucks. Clearly show that the societal benefits of switching to ZE trucks far outweigh the costs. Results from the health and climate analyses in this report show that cumulative benefits from switching to ZE trucks clearly outweigh the costs, as shown in other contexts in recently published studies (e.g., see ICCT, 2019) [242]. However, health and climate benefits do not accrue directly in the short term to most people who use trucks for their business. People may therefore resist this transition if they believe that they are bearing the costs of this critical transition. It is also important to explore and demonstrate, via targeted case studies and working in partnership with OEMs, that total cost of ownership will decrease with ZE trucks, as direct benefits will include fuel and maintenance savings with payback periods ranging from a couple of years to 4–5 years depending on truck type and use. Finally, depending on technology, some ZE trucks may have some substantial impacts on traffic and road safety. These benefits should be quantified to formulate more efficient policies.

5. Sustained public funding will be needed in some sectors to make up for the difference in purchase price between ZE and conventional trucks. These programs should target primarily independent owners in selected industries. To reduce the drain on the state budget, they should be temporary: they could expire after a certain number of ZE vehicles has been sold, enough for that market niche to be sustainable. An alternative to grants is lease programs with an option to buy. Such programs could allow a potential owner to experience and assess an unfamiliar technology.
6. Smart policies should be developed to support the transition to ZE trucks. They include increasing taxing ICEVs and fossil fuels to create revenue streams that will help pay for initial incentives. In addition, subsidies for the acquisition of ZE trucks could be combined with taxes on conventional trucks to further foster the adoption of the former. Another obvious source of funding is carbon markets (such as cap and trade).
7. As mentioned in other sections of this report, merely putting in place policies to foster the adoption of ZEVs is not sufficient. The refueling and maintenance infrastructure need to be developed, along with the workforce that will support this infrastructure, whenever possible in partnership with the private sector and electric utilities. In particular, emerging freight patterns (related for example to the shift toward online shopping, which was accelerated by the COVID-19 pandemic) should be studied to anticipate the demand for refueling infrastructure.
8. During the transition to ZE emission trucks, continued progress on energy efficiency for conventional and ZE trucks alike and improving compliance with efficiency standards should be pursued because conventional and ZE trucks will continue to co-exist for at least a couple of decades in California, if only because of interstate truck traffic and international truck traffic with Mexico. Continued progress can be made in engine efficiency, hybridization, reductions in aerodynamic drag, and reductions in tire rolling resistance. The latter applies to both conventional and ZE trucks. It is also important to enforce current and future emissions standards. To facilitate this measure, on-board diagnostics similar to those that come with truck engines of model year 2013 and newer, coupled with remote data access could be mandated.

8 Vehicle-Miles Travelled

8.1 Introduction

California's total vehicle-miles-of-travel (VMT) are the product of the decisions that households and businesses make on a daily and longer-term basis. Household decisions about where, when, how often, and by what mode to travel determine their VMT; these decisions are conditioned by longer-term decisions about residential location and car ownership. Business decisions about shipments of material inputs and delivery of products or services determine VMT of goods movement. Business decisions about location influence household travel, for employees and customers, as do policies on remote work and online shopping. In other words, VMT is the product of the complex system of modern living.

Shown below in Figure 8.1 are the general drivers of VMT and VMT growth, including socioeconomic, land use/built environment, transportation system, and travel demand factors.

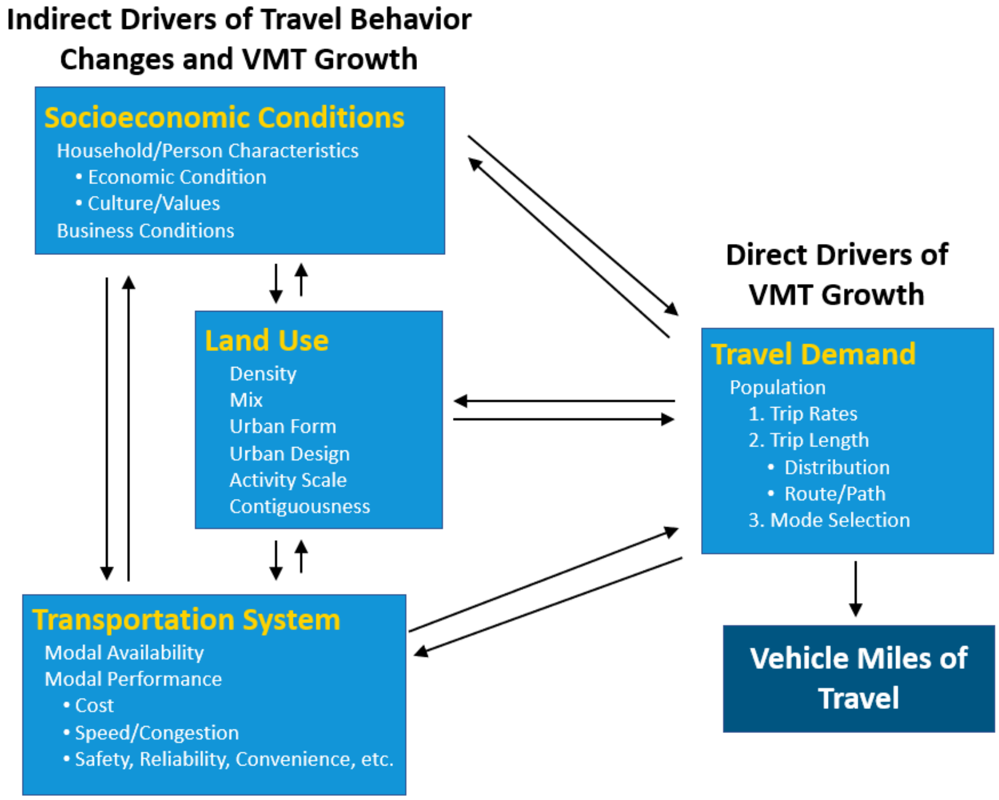

Figure 8.1. Factors Influencing Vehicle Miles of Travel (Source: Polzin, et al. 2004 [278])

Reducing VMT requires a shift in the decisions that households and businesses make. Policy can reduce VMT by shifting decisions in two ways: 1) by making it possible to reduce the use of vehicles through improved infrastructure and alternatives; and 2) by encouraging a reduction in the use of vehicles through incentives to use alternatives (“carrots”) or disincentives to drive (“sticks”) or both. To achieve a significant reduction in VMT both approaches are necessary; encouraging a reduction in driving is not likely to succeed if households and businesses have no alternative to driving, and making it possible to drive less is likely to lead to little reduction unless households and businesses are nudged to take advantage of the opportunity.

In this analysis, we consider a suite of policies that could be used simultaneously to achieve VMT reductions by enhancing the alternatives to driving and encouraging the use of these alternatives. In many, but not all, of the cases the policies that we consider are expected to be supportive of each other. We discuss these interaction effects between policies later in this section.

THREE REVOLUTIONS IN FUTURE MOBILITY

Emerging trends in transportation along with electrification include vehicle sharing and automated driving, sometimes known as the “three revolutions” in transportation. While these trends are seen as more or less inevitable to progress further, the pace and nature of them remains unclear. Electrification is a clear trend, where while growth in EVs in the U.S. slowed some in recent years, an acceleration is now expected based on anticipated changes in U.S. policy to more closely align with California. Automation, however, has been somewhat slower to become a major reality than projected several years ago, but with major investments still being made by several of the world’s largest companies. Meanwhile, shared use of vehicles through carsharing, ridesharing, and shared TNC rides are trends that have had some fits and starts in recent years, with significant slowing due to the COVID crisis.

Given the uncertainties with how these trends will unfold and interact over time, it is difficult to assess their impacts on transportation energy use and emissions. Various studies have shown for example that automation will have a myriad of complicated impacts that will in some cases reduce energy use and emissions and in other cases increase them. Benefits of automation may include those from vehicle platooning (reduced drag), eco-driving, and reduced accidents among others. Furthermore, access to a range of vehicles such as through shared use vehicles can lead to “vehicle right sizing” whereby smaller and more efficient vehicles can be selectively used where appropriate, reducing emissions from some trips. On the other hand, reductions in the cost of travel through electrification and automation could induce demand for additional travel, thus adding VMT, energy use, and emissions. Automation may allow for higher highway speeds, with potential increases in emissions, as well as travel by new user groups such as the elderly and handicapped that could become less shut in to their homes. This has implications for improved equity in mobility and access, but potential additional system use and associated emissions. Also further use of TNC vehicles includes some travel without passengers, or vehicle “dead-heading,” both for travel between picking up passengers and including trips for TNC EVs to visit charging stations, and these impacts can be significant in terms of energy use and emissions.

The various forces related to these trends will thus play out in complex ways, and are likely to vary in different settings and regions. Additional complexities including evolving TNC policies in California that are rewarding the use of clean fuel vehicles and shared rides, and potential additional factors related to the extent to which fully automated vehicles will be allowed outside of city centers. The extent and impact of these policies will shape both the direction and emissions implications of these future transportation system evolutions.

The analysis methodology for the VMT "policy shift" aspects of the LC1 scenario combines consideration of several different strategy types discussed in the sections above, that fall under 5 more general categories. In order to define the LC1 scenario for the overall project effort, it was necessary to establish a target level of per-capita VMT reduction so that the rest of the LC1 scenario involving vehicles and fuels could be defined. Based on literature reviews of potential strategy impacts and expert judgement, the project team identified an initial goal of determining what combinations of strategies could deliver a net per capita VMT reduction of 15% relative to the business-as-usual (BAU) baseline, and then to consider what further reductions might be possible beyond that. This was not meant to indicate the limit of VMT reduction potential, but simply an initial estimate of what a relatively aggressive and carefully crafted set of strategies and policies could potentially achieve through 2045.

The various strategies examined for their potential implementation and impact over time are:

- Built Environment:
    - Transit-Oriented Development/Densification
    - Active transportation
    - Public transit investments and expansion
- Transportation Pricing:
    - Gasoline/diesel taxes
    - VMT based road fees
    - Dense urban area cordon zones
    - Other road pricing such as high-occupancy toll (HOT) lanes for congested corridors
    - Parking pricing
- Transportation Demand Management (TDM):
    - Employer-based TDM strategies - telework
    - Employer-based TDM strategies - carpooling
- Shared Micromobility / Pooling:
    - Shared micromobility
    - TNC pooling incentives

The first three strategies shown in the list under the Built Environment category are considered shifts that would be fundamentally tied to changes in land use planning and policy as well as transportation infrastructure. The other strategies considered are more discrete in many respects, but also interrelated, making for a complex analysis space. For purposes of this analysis these strategies are analyzed discretely rather than in a fully integrated framework, but potential interactions between these strategies are discussed generally further below. Also described are more specific types of new policies and policy extensions that would be needed to support the success of these strategies. We do not explicitly examine the impact of the strategy titled "Other road pricing such as HOT lanes for congested corridors" as it could in some ways be duplicative of the VMT road fees and/or cordon pricing policies and is also highly site specific (highway corridor level) in terms of its potential impact.

In order to assess the VMT reduction impacts of these strategies on a per-capita basis, the project team developed an extensive Excel-based spreadsheet modeling framework that translates census tract level (there were 8,059 census tracts in California for the 2010 census) information to assign each census tract a dominant place type per the typology described in Table 8.1, and defined by place type definition rules that are further explained in Appendix (VMT). Using population, VMT, and other household data applied to the census tracts, the VMT analysis model (about 100 MB in total file size) calculates average per-capita VMT and allows for analysis of: 1) changes in population over time at the census tract level; 2) changes in place types at the census tract level over time; and 3) resulting changes in VMT by place types aggregated up through the census tracts. This is the primary basis for analyzing the impacts of the Built Environment measures in this analysis.

Table 8.1. VMT by Place Type "Importance" Weighting by Analysis Year

		2020	2025	2030	2035	2040	2045
Code	Place types	Base Year					
1	Urban, low transit	20.81%	16.03%	15.61%	14.86%	14.33%	13.57%
2	Suburb, MFH	22.06%	26.46%	26.43%	27.43%	28.16%	28.91%
3	Central city	0.59%	1.06%	1.19%	1.25%	1.31%	1.40%
4	Rural	10.28%	11.48%	11.34%	11.15%	11.18%	11.07%
5	Suburb, SFH	35.19%	34.05%	34.69%	34.55%	34.15%	33.91%
6	Urban, high transit	6.77%	6.77%	6.56%	6.54%	6.60%	6.81%
7	Rural-in-urban	4.29%	4.16%	4.18%	4.21%	4.26%	4.33%
	Total	100%	100%	100%	100%	100%	100%

The census-tract level place type analysis is then combined with other VMT strategies to achieve larger combined impacts than any measure could achieve by itself. Thus, the resulting calculations from the Built Environment category, when combined with analysis of the other nine strategies, results in a set of per-capita emission reduction estimates by analysis year. These estimates are shown in Table 8.2 and Figure 8.2 below.

Table 8.2. Analysis Results - Per-Capita VMT Reductions Over Time (5-Year Changes) by Strategy

	2025	**2030**	**2035**	**2040**	**2045**	**Cumul. Total**
Built Environment: - TODs and densification - Active transportation - Public transit investments	1.2	1.1	0.8	0.9	0.8	4.7%
Pricing - Dense Urban Area Cordon Zones	0%	1.2%	0.6%	0%	0%	1.8%
VMT fee $0.10/mile *VMT fee $0.15/mile*	0% *0%*	0.9% *0.9%*	-0.2% *-0.2%*	3.1% *4.7%*	-0.2% *-0.2%*	3.6% *5.2%*
Pricing - Parking Pricing	0.12%	0%	0%	0%	0%	0.12%
Employer-based TDM Strategies - Telework	2.51%	0.00%	0.00%	0.00%	0.00%	2.51%
Employer-based TDM Strategies - Carpooling	0.70%	0.00%	0.00%	0.00%	0.00%	0.7%
Shared Micromobility	0.03%	0.00%	0.00%	0.00%	0.00%	0.03%
TNC Pooling Incentives	0.3%	0.5%	0.2%	0.2%	0.3%	1.6%
TOTAL PER-CAPITA VMT REDUCTION WITH All MEASURES BY 2045						15.0%

Note: A few rows may not total exactly because of rounding. The final column represents the correct overall total reduction.

As shown in Table 8.2 and Figure 8.2, the most potent categories for VMT reduction are the combined group of pricing strategies, changes to the built environment through urban shifts and developments over time, and TDM strategies (especially telework). These can be combined along with smaller contributions from the shared micromobility and pooled TNC operations category to contribute to overall per-capita VMT reductions over time.

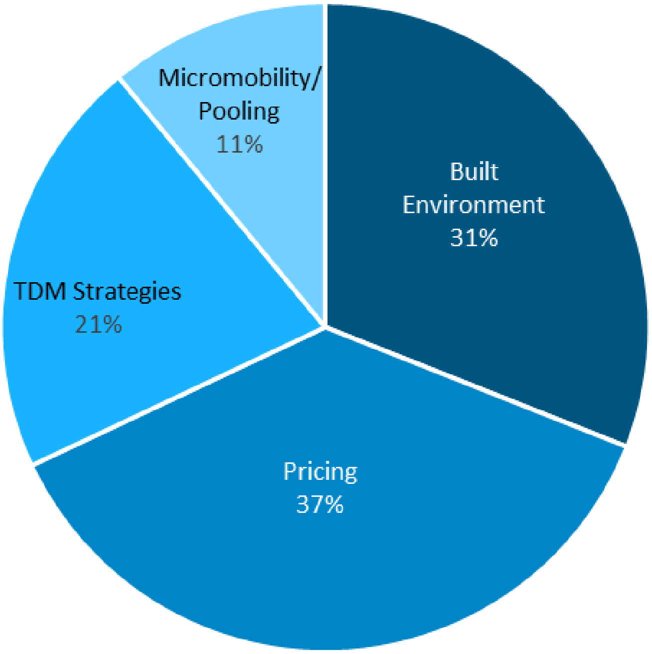

Figure 8.2. Shares by Category of VMT Strategy Per-Capita Reductions

Overall, we find that to achieve the LC1 defined target of at least 15% per capita VMT reduction by 2045 relative to the BAU, an integrated policy strategy is required, combining all of the main elements examined here. The combination of all of the examined strategies results in a total estimated per-capita VMT reduction by 2045 of 15-17%, depending on the level of a VMT based road fee starting around 2030 ranging from $0.10 to $0.15 per mile. This result implies that the state could achieve the 15% per-capita VMT reduction included in the LC1 scenario by pursuing a strategy that combines the elements considered here. Additional reductions beyond the 15% level could include the higher level of VMT-based road user fees after 2030 (above $0.10/mile), as well as corridor-level HOT lane programs that may increase or decrease VMT depending on their overall effects on travel times as discussed below.

We note that the actual impacts of combining groups of strategies and policies in this way are hard to fully anticipate until initial experiences determine how they interact. Further details of the analysis of these strategies, including the use of various VMT response elasticities and other methods from the literature are provided in Appendix 14.2. We describe important general policy actions and directions to support these strategies, and potential policy interactions below.

8.2 Scenarios

8.2.1 VMT Topic Policy Scenario Descriptions

In order to realize the potential goals of these strategies in reducing per-capita VMT by 2045 in the LC1 Scenario compared to the BAU, various public policies need to be extended or enacted to reinforce the travel behaviors and create the other changes that are needed.

The California policy environment is a complex combination of state-level regulation and department-level policies, policies and directives implemented at the regional or MPO level, county-level policies, and municipal policies. These all come to bear in various ways on policies that influence VMT as described in the BAU section of this report. There are then a host of policy implementation issues around the design and schedule for implementation of specific policies, public acceptance, decisions about use of revenues from pricing policies, equity and EJ aspects, administration and enforcement, and potential for unintended policy consequences.

The policies examined here include the following, which are described in some detail below:

- Built environment and land use/planning:
  - Transit-Oriented Development/Densification
  - Active transportation
  - Public transit investments and expansion
- Transportation pricing :
  - Gasoline taxes – could be raised in future but just done recently
  - Shift to general VMT based road fees as # of EVs grows and gas tax revenues decline
  - Combinations with other road pricing policies – corridor congestion pricing/HOT lanes
  - Dense urban area cordon pricing
  - Parking pricing policies
- TDM strategies:
  - Employer-based telework policies – incentives, perks
  - Employer-based carpooling policies – parking, incentives, penalties, correct hidden subsidies
- Micromobility / Ridesharing and pooling:
  - Shared micromobility – subsidize operations? Provide infrastructure
  - TNC ride-sharing incentives and peer-based carshare

8.2.2 Built environment and land use/planning policies

Bringing about changes to the built environment that are necessary for reducing VMT requires changes in policy at the state, regional, and local levels. Land use policies are traditionally the responsibility of local governments, both cities and counties, which influence land development through zoning and other mechanisms. Local governments also have primary responsibility for local streets, including investments in bicycle and pedestrian infrastructure. State policy such as SB375 and SB743 has changed procedures for regional and local planning to focus on VMT reduction. These changes are contributing to the adoption of local policies that are beginning to change the built environment in ways that should reduce VMT [279]. The state is also exerting influence over local policy by enticing local governments with funding for VMT-reducing projects (e.g., California Climate

Investments programs) and by compelling local governments to allow higher densities through state planning law (e.g., density bonus requirements, various legislation allowing accessory dwelling units)

To ensure that the built environment changes in ways that will contribute to sufficient reductions in VMT, the state may need to strengthen these efforts, in addition to adopting new strategies. Other strategies that that could be effective include:

- State-mandated “up-zoning” to allow higher densities in transit-rich areas, coupled with policies to deter the displacement of lower-income residents.
- State-mandated “down-zoning” in rural areas to preserve working and natural lands while preventing the outward growth of urban development.
- The creation of VMT offset banks to provide a flexible mechanism for mitigating VMT impacts in the development review process under CEQA.
- Restructuring of the state’s transportation finance system to give higher priority to transit and active travel to better align with climate policies (Sciara and Lee, 2018) [280]

Discussions of possible state policies to reduce VMT are provided in Boarnet and Handy (2017) [281] and Byars, Wei, and Handy (2017) [282], as well as a forthcoming report for the California State Transportation Agency.

8.2.3 Transportation pricing policies

Transportation pricing policy is a complex and often controversial area. Transportation pricing policies involve complex implementation issues around public acceptance, social equity and decisions about use of revenues from pricing policies, administration and enforcement, and how to provide low-income and other fee waivers, among others. Described below are the broad transportation pricing strategies included in this analysis. We note that other pricing policies are also possible including local corridor HOT lanes, but the impact of these on actually reducing VMT on a statewide basis are uncertain as we note.

8.2.3.1 Fuel tax and VMT-based Road Usage Fee

This policy combines a fuel (i.e., gasoline and diesel) tax starting in 2030 with a distanced-based road-usage fee in 2040. Unlike other VMT policies laid out in this report, these two pricing policies are quite specific in terms of how an increase in the gas tax or distance-based road-user fee would affect VMT. This specificity should not be confused with certainty, as it pertains to the elasticity parameters. There is considerable uncertainty associated with the elasticity of VMT with respect to pricing changes. Nevertheless, the values in this section should provide a good estimate of the order of magnitude of pricing change needed to reduce VMT per capita by around 3.5-5%. It is also important to note that while the modeling framework assumes the policies in this report are additive in terms of their impact on VMT—making it more expensive to drive (i.e., consume vehicle miles)—pricing, specifically pricing private vehicle usage, is critical to unlocking the benefits of the other policies.

Given the state of California recently increased the state’s gasoline tax by $0.12 per gallon and the diesel tax by $0.20 per gallon (*SB-1 Transportation Funding*, 2018) [283, p. 1], we assume that an additional increase in the fuel tax is not feasible in 2025. Rather, an increase in the gasoline/diesel tax is proposed for 2030.

As with all taxes, fuel tax increases tend to be unpopular. However, research indicates that when voters are told the specific uses of new tax revenues, the tax increases are more likely to pass [284]. Hence, tying future gasoline tax increases to specific infrastructure projects (e.g., electric vehicle charging infrastructure, maintaining surface streets in urban areas, etc.) or even possibly greenhouse gas reduction benefits, may increase the palatability of gasoline tax increases.

The implementation of a fuel tax increase at the state level is relatively straightforward as this is a well-known lever for lawmakers. The methodology section includes specific parameters for elasticity of VMT with respect to increases in the fuel tax, for each place type. While these parameters were estimated using data from California, they should still be treated with a degree of uncertainty by state lawmakers. Given the elasticity parameters and a forecast of the percentage of gasoline fueled vehicles on the roadway, lawmakers can estimate the impact of specific gasoline tax increases on VMT. The results in the methodology section indicate that an increase in the gasoline tax of $0.40 is likely to decrease VMT by about 1% in 2025; however, given the significant reduction in the share of gasoline fueled vehicles on the road between 2025 and 2045, the $0.40 tax is likely to decrease VMT per capita by only 0.2% in 2045, even if the $0.40 tax is adjusted for inflation. As such, increasing fuel taxes is really only a potential solution in the next 10-15 years; it is not a long-term solution for reducing VMT.

Although not considered in our analysis, a fuel tax is likely to speed the transition to alternative fueled vehicles. While this has the additional downside of decreasing the ability of the gas tax to reduce VMT, it has the more important benefit of incentivizing travelers to use more sustainable travel options.

Like the gasoline tax in the past, a distanced-based road user fee would likely be implemented at the state level on all vehicles traveling in California or at least all vehicles registered in California. Assuming the state is not initially interested in dynamic, road-dependent pricing, a VMT fee would be straightforward to implement from a technology perspective. The Rand Corporation lays out several ways to operationalize/implement a VMT fee. In one method, vehicles would be subject to odometer readings during emissions inspections. Of course, users could self-report their odometer readings on a quarterly or annual basis and then these readings would be validated during vehicle inspections or emissions readings. This method is the most straightforward and privacy sensitive. One potential issue is that California could not charge out-of-state vehicles for road usage and Californians may be charged for driving on roads in other states. In another method, users would utilize onboard units (OBUs) that connect to a vehicle onboard diagnostic (OBD) port, cellular communications, and/or a GPS receiver. OBD ports are standard in all cars produced after 1996. Insurance agencies currently employ this method for mileage-based insurance options. This option is less privacy sensitive, but it would permit more advanced and dynamic pricing strategies such as cordon pricing and high-occupancy tolling.

Unlike the gasoline tax, the VMT road fee would apply to all light-duty vehicles in California through 2045. This makes it a significantly more effective policy for reducing VMT than the gas tax. The methodology section includes specific parameters for the elasticity of VMT with respect to increases in the cost of driving per mile. While these parameters are uncertain, they provide an estimate of the order of magnitude VMT fee needed to reduce VMT per capita by 3.5 to 5%. To decrease VMT per capita by 3.5% in 2045, the results indicate that a VMT fee of $0.10 per mile (in 2020 dollars) is needed, representing an approximate increase of 18% in the cost of driving per mile. While this is a fairly substantial increase in the cost of driving, it is likely needed to make a significant dent in VMT in California. A further level of per mile fee of $0.15 was also examined, reaching the higher level of about a 5% per-capita VMT reduction for this measure.

Along with Oregon, the state of California has piloted mileage-based road user fees[17]. In addition to being used to potentially decrease VMT, the mileage-based road user fee is possibly a more financially sustainable road maintenance and rehabilitation funding mechanism than the gas tax given the increased efficiency of gasoline-fueled vehicles and their decreasing market share in California.

The state budget impacts of these two policies would be substantial, with very large increases in revenue from both the gas tax and the VMT-based road usage fee. Given that SB1 is expected to generate $4.4 billion in additional annual revenue for the state and SB1 increased the state's gasoline tax by $0.12 per gallon and the diesel tax by $0.20 per gallon (*SB-1 Transportation Funding*, 2018), the proposed $0.40 per gallon fuel tax proposed would generate closer to $10-$15 billion dollars in additional annual revenue. These revenues will decrease as the market share of gas-fueled vehicles in the state decreases.

The expected annual revenues from a $0.10/mi road-usage fee would likely exceed the proposed fuel tax revenues. However, given the lack of data on real-world distanced-based road-usage fees, forecasting revenues is quite difficult.

Regarding the equity implications of the fuel tax and the VMT-based road-usage fee, research shows that low-income car users will be the most impacted by the proposed fuel tax increase and the proposed distanced-based road-usage fee. Low-income car users tend to not have other options to travel and the trips they make via cars are more likely to be non-discretionary, as such they are unlikely to be able to change their behavior and avoid the increased costs associated with a distanced-based road-user charge. Moreover, as alternative fuel vehicles tend to be more expensive than gas-fueled vehicles, low-income individuals are less able to purchase alternative fuel vehicles.

While the current analysis assumes that all users (independent of economic status) pay the same fuel taxes and road-usage fees, a direct means to address equity in transportation pricing would involve a progressive road-usage fee (and possibly progressive fuel taxes) where the higher an individual/household's income, the higher the fee/tax they pay. It is even feasible to determine progressive fees/taxes that have a neutral impact on VMT reductions compared to the base case in this report. Regarding political feasibility of a progressive fee/tax, it is worth noting that the state already has a progressive vehicle registration fee wherein more expensive vehicles (in terms of purchase price and purchase date) pay a higher registration fee.

Moreover, given the state will receive large revenues from the proposed fuel tax and road-usage fee, these revenues could be used to decrease the negative equity impacts of the fuel tax and road-usage fee policies. The most direct method would involve a dividend to residents of the state of California, wherein the state collects the revenues and spreads the revenue or part of the revenue to residents of the state. These dividends could be progressive where lower income individuals/households receive larger dividends, or every individual/household could receive the same amount. The state could also use the increased revenues to invest in alternative

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[17] http://www.caroadcharge.com/about

transportation modes, particularly in low-income communities, such as rail or bus transit and active transportation modes.

8.2.3.2 Corridor congestion charges

We note here that the project team also considered the potential for corridor type congestion relief schemes such as HOT lanes to reduce VMT. However, the literature suggests fairly weak and very localized effects on overall VMT from these types of projects, which are difficult to analyze statewide. We thus consider them additional strategies that could be considered on a regional basis, perhaps more for revenue generation to support regional transportation improvements than for VMT reduction through any expected additional carpooling.

8.2.3.3 Cordon Pricing Implementation in California Major Cities

The cordon pricing strategy described above assumes that this would be implemented in the largest and densest urban areas in California, including San Francisco, San Jose, Los Angeles, San Diego, and Sacramento. It also assumes improvements in transit in these regions to provide alternative transit modes to driving, along with infrastructure improvements to support shared and private micromobility as well as active modes of transportation.

In order to achieve the types and magnitudes of enduring VMT reductions seen in places like London, England and Stockholm, Sweden, the cordon prices would likely need to be of similar magnitude given that the economies of these countries and the U.S. are different but in a similar developed country class. At present the toll is about $18 per vehicle in London from 7am to 10pm, with residents getting a 90% break and some discounts for low-emission vehicles. In Stockholm the pricing is somewhat lower and varies more dynamically with no charge from 6:30pm to 6:00am and then charges of around $2 per vehicle at relative off-peak times like mid-day to about $5 per vehicle during commute hours.

With a “strong” cordon pricing policy such as in the London area with tolls in the $15-20 range during peak periods and only somewhat lower during mid-peak times, we estimate an approximate 1.8% reduction in per-capita VMT statewide by 2035 if the policy were to apply to all of the suggested areas. A somewhat weaker policy, more analogous to Stockholm, would yield lower reductions, perhaps more on the order of 1%, but would be more politically feasible and face less public resistance. Once again, this presumes significantly improved alternatives to automobile travel in these areas by 2030-2035.

Actions suggested for California to consider as steps to implement this policy include first creating regional transit authorities like San Francisco County Transportation Authority has done with the “Treasure Island Mobility Management Agency” in each area, to study the implementation of cordon pricing in those areas. Los Angeles also has an ongoing pilot program called Express Travel Choices, to study cordon pricing along with other congestion pricing strategies. This includes studying pricing models and examining their equity and environmental justice aspects.

The second step of implementation for cordon pricing is thus to study each of the key regions with its unique conditions, including access routes to the city centers, infrastructure changes needed to avoid bypassing the cordon toll areas, the method of collecting fares (e.g., Fastrak Bay Area), determining the initial level of fees and timing, establishing exclusions (e.g., city center residents, low income, reductions for clean-fuel vehicles, etc.) based on detailed studies.

In addition, a communications campaign would be needed specific to each region to inform the public significantly in advance of implementation, emphasizing the congestion relief elements and the use of the collected revenues, as well as methods to mitigate potential negative economic equity and social justice aspects, and improved transit and other driving alternatives. The above analysis assumes that it would take until around 2030 to implement the cordon pricing as it would take several years to complete the above steps. Also, as in London, the fees and nature (flat or dynamic, etc.) could be adjusted over time every few years to calibrate the measured VMT reduction response and other behavioral adaptations.

We note here again, this type of flat pricing policy is generally regressive by nature but that can be corrected depending on how the revenues generated are used. This is discussed further in the equity section below.

8.2.3.4 Parking Pricing

Parking pricing can take multiple forms, but it is generally implemented within urban areas. Parking pricing increases the cost of vehicle storage at a destination, and thus increases the overall cost of using a personally owned vehicle for travel. Parking pricing policies can have several goals. Naturally, one of the first goals of parking pricing is to raise revenue, either for the municipality or the private parking entity. Another key goal of parking pricing is to ensure parking availability in areas where it is scarce. If parking is underpriced or free, it can become overused and congested, particularly in popular destinations. This forces other personal vehicle drivers to park farther from their destination. Parking pricing is meant to prevent such situations. Raised parking pricing causes some travelers to change their modal choice, taking public transit, TNCs, walking, bicycling, or forgoing travel to the destination.

Parking pricing can be particularly effective in the employment environment, where travel to the location is routine and required, and the storage period time for the vehicle is long. These costs can raise the overall commute costs on workers considerably. Elevated parking costs force some travelers to consider alternative commute modes. This mode shift is typically toward public transit, which can provide routine trips at a low cost during peak periods. This mode shift is the primary mechanism of VMT reduction. However, parking pricing is limited in scope and effectiveness on a grander scale because it can only be executed effectively in urban areas. These urban areas also need to have considerable land-use density, where parking pricing can be implemented on the street or in parking garages. Lower density suburbs, which abound with business parks and private lots, also offer an avenue to implement parking pricing. Not surprisingly, parking pricing is not feasible in rural environments, and it is unlikely to have any VMT impact in areas where mode shift is not possible. Despite these limitations, parking pricing can be an effective policy tool within urban environments and can reduce VMT. This may lower peak congestion and enable higher public transit ridership in regions where there is more intensive land use. Action suggested for California is to employ more dynamic parking pricing initiatives, similar to SFpark, particularly in areas with higher land-use density [285].

8.2.4 TDM policies

8.2.4.1 Employer-Based Carpooling

For decades, carpooling has been used by numerous public agencies and employers as a strategy to address a range of climate, environmental, and congestion mitigation goals, while simultaneously increasing roadway and parking capacity. Carpooling allows travelers to share a ride to a common destination and can include several forms of sharing a ride, such as casual carpooling and real-time carpooling. Because carpooling reduces the number of automobiles needed by travelers, it is often associated with numerous societal benefits including: 1) reductions in energy consumption and emissions, 2) congestion mitigation, and 3) reduced parking infrastructure demand [286]. Nevertheless, it is important to note that carpooling could lead to induced demand due to reduced travel times and costs. Thus, this should be factored into calculations of the net VMT impacts of this mode.

For employers, carpooling can: 1) reduce the need for parking, 2) increase the productivity and morale of employees, and 3) provide financial and tax benefits for employers. By reducing the number of vehicle trips, public and private sector employees can reduce parking demand, thereby saving capital costs of $15,000 to $45,000 US per parking space (depending on design and land availability) and operational costs of approximately $360 to $2,000 US annually per parking space [287], [288].

At present, national carpooling policy offers a number of financial and tax benefits to both employers and employees to promote this mode. Section 132(f) of the U.S. Internal Revenue Code provides a way for employers to provide parking, public transit, vanpool, and bicycle expenses on a tax-free basis. The monthly cap for the parking, public transit, and vanpool benefits are set at $260 US/month and both are subject to annual cost of living increases. Previously, employers could deduct the subsidy portion of a commuter's expenses that were paid for by the employer. However, this tax benefit was eliminated with the passage of the Tax Cut and Jobs Act of 2017, which removed this employer deduction. Employers can still subsidize these expenses, but they can no longer deduct the subsidized portion of their commuters' expenses (Shaheen et al. 2018; Shaheen et al 2019) [289], [290].

A number of states have implemented state level commuter tax benefits and tax credits for carpooling. For example, Maryland offers a tax credit of 50% of the eligible costs of providing commuter benefits. Employers and non-profits [501(c)(3) and (4)] can claim a credit for 50% of the eligible costs up to a maximum of $100 US per employee per month. This tax credit can be taken against state personal income tax, corporate income tax, or the insurance premium tax and is applicable to public transit passes, employer vanpool programs, guaranteed ride home programs, and parking cash out programs (Comptroller of Maryland 2018). For more on parking cash out, see: Shoup 2011 [287].

In Georgia, employers can receive an annual $25 US tax credit for each employee that uses a federal qualified transportation fringe benefit. To qualify, employees must use the commute alternative at least 10 times per month. This credit is available to employers that pay the Georgia corporate income tax and provide public transit pass subsidies or vanpool subsidies for employees or qualified carpool/vanpool parking on or near the business premises (Georgia Code 48-7-29.3). Furthermore, in Washington state, employers and property managers who are taxable and provide financial incentives to their employees for carpooling (carrying two or more passengers), carsharing (e.g., Zipcar, GIG car share), public transportation, and non-motorized commuting before January 1, 2024 are allowed a credit against taxes payable or amounts paid to or on behalf of employees up to $60 US per employee per fiscal year. The maximum eligible tax credit is $100,000 US per employer or property manager per fiscal year.

From a national and state policy perspective, carpooling incentive programs may incorporate a variety of means to encourage employees to carpool. Common incentives include direct cash incentives, reduced cost or free parking, preferred parking, or reward programs (such as prize drawings) [291]. A number of studies have tried to document the role of incentives and disincentives. For instance, a study by Shoup (1997) [292] found that parking cash out programs where employers are required to give their employees a choice to either keep their employer-paid parking space at work or to accept a cash payment and give up the parking space, increased carpooling by 64%, while decreasing single occupant vehicle (SOV) travel by 17%.

A study of Georgia's Cash for Commuters program in which new carpoolers were offered a $3 per day incentive for 90-days to try carpooling found that 57% continued to carpool 18 to 21 months after the initial incentive period (Georgia Department of Transportation 2009) [293]. This study highlights the role that short-term incentives can have in encouraging a longer-term modal shift.

Local and regional governments also can support carpooling in a number of ways. They can partner with private sector employers and carpooling providers to support local and regional ridematching efforts. They also can provide incentives and sponsor guaranteed ride home programs for carpooling. In addition to these policies, local and regional governments should consider:

- Implementing parking reforms, such as pricing parking (see discussion above), eliminating parking minimums, and implementing parking cash-out programs;
- Institute road and curb pricing strategies, such as road tolls, congestion fees, and other charges (see above);
- Implementing trip reduction and TDM ordinances; and
- Funding carpooling infrastructure and support high-occupancy vehicle (HOV) priority through HOV lanes, park-and-ride facilities, encourage the inclusion of carpooling parking at new and existing facilities, and implement signal prioritization for higher occupancy vehicles.

For more details on carpooling policy, see Shaheen et al. (2018) [289].

8.2.4.2 Employer-Based Telework

Employer-based telework policies could be implemented in California through regional/local agencies, particularly in central city urban and urban high public transit place types. Plan Bay Area, for example, has proposed a telework policy (on any given workday) for large employers in the Bay Area. Building upon the significant shift to work from home during COVID-19, this proposed Plan Bay Area strategy would include mandating large employers to have at least 60% of their employees telework on any given workday. As currently proposed, this requirement is limited to large office-based employers whose workforce can work remotely. According to the Draft Blueprint, this policy would enable an increase from the projected telecommute share of 14% (as noted in the Draft Blueprint) to up to as high as 25%, recognizing that half of the workforce has a job that must be completed in-person (and would not be eligible for telework).

In suburban and rural areas, local agencies could move to require similar policies. In this study, we applied parameters based on a Gartner survey of 317 CFOs conducted in April 2020. This survey suggested that 74% of companies plan to permanently shift to more remote work after the COVID-19 pandemic. Approximately 27% of the CFOs said that they would remain 5% in remote work, and another 25% would remain 10% [294]. This could be translated to a range of 5% to 15% of teleworkers in suburbs and rural areas, for instance. If the state, regions, and local agencies wish to further increase telework shares, percentage distributions by place type could be adjusted upwards. To ensure that these policies are viable, California might consider providing resources (e.g., access to satellite telework facilities locally) and tax incentives to employers for shifting their workforce policies (Shaheen et al 2020). This could also be combined with employer based-parking policies (e.g., parking cash out) (Shoup 2011) [287].

8.2.5 Shared micromobility/pooling policies

8.2.5.1 Shared micromobility

Shared micromobility—the shared use of a bicycle, scooter, or other low-speed mode—is an innovative transportation strategy that enables users to have short-term access to transportation on an as-needed basis. Shared micromobility includes various service models and transportation modes that meet the diverse needs of travelers, such as station-based bikesharing (a bicycle picked-up from and returned to any station or kiosk) and dockless bikesharing and scooter sharing (a bicycle or scooter picked up and returned to any location).

Early documented impacts of shared micromobility include increased mobility, reduced GHG emissions, decreased automobile use, economic development, and health benefits. To further expand active transportation modes, such as shared micromobility, the state should consider policy and legislation to support its growth, as noted below.

There are a number of policies that are applied to shared micromobility, particularly at the local level including: fees, curb space management approaches (e.g., local ordinances, permits, supportive infrastructure); social equity requirements; and data sharing. To start, many cities charge operators a variety of fees for allowing the placement of shared micromobility devices in the public rights-of-way. These fees can include per trip taxes, application fees, and annual fees based on the number of devices placed in the public rights-of-way. Portland, Oregon, for example, charges a $0.25 tax per scooter ride. The funds are placed in a “New Mobility Account” to pay for program administration, enforcement, and infrastructure improvements. Supportive infrastructure, dedicated and protected bike lanes, could help to expand the use of shared micromobility (Shaheen and Cohen 2019) [290].

Curb space management is a term used to describe a policy and transportation design approach that requires curb access to be planned, designed, operated, and maintained to enable safe, convenient, and multimodal access for all transportation users. Shared micromobility curb space is typically allocated through a combination of formal and quasi-formal processes. Some cities establish formal policies that may be written, codified by local ordinances, or allocated through an application process, whereas others use quasi-formal processes including pilot programs and case-by-case approvals from administrative staff. (Shaheen et al 2020) [295].

Social equity is another important area for shared micromobility policy and should include:

- Expanding shared micromobility access to people with disabilities, underbanked households, and other communities with special needs;
- Requiring shared micromobility to be equally distributed in the rights-of-way into economically disadvantaged areas; and
- Providing discounts or subsidies for low-income users based on income qualifications (Shaheen et al 2017; Shaheen and Cohen 2019) [296], [297].

Data sharing is a requirement of many local public agencies as a condition to operating in the public rights-of-way. Standardized and open data allows public agencies to: 1) better understand shared micromobility impacts (e.g., VMT, GHGs); 2) identify gaps in the transportation network; 3) monitor equitable service standards; and 4) offer multimodal, real-time transportation information through smartphone apps, websites, and other platforms. Beginning in 2015, the North American Bike Share Association adopted an open data standard, known as the General Bike Share Feed Specification (GBFS) that makes real-time bikesharing operational data feeds publicly available in a standardized format. GBFS does not include historical usage data or other personally identifiable information.

More recently, Los Angeles has led the development of the Mobility Data Specification (MDS) in conjunction with data scientists from other cities to supply operators with a single, open-source application programming interfaces (APIs) they can use to share required real-time data about their services. MDS is a data and API standard that allows a city to gather, analyze, and compare real-time and historical data from shared mobility service providers. The specification also serves as a measurement tool that helps enable enforcement of local regulations. MDS includes data such as: mobility trips (and routes); location and status of equipment (e.g., available, in-use, and out-of-service); and service provider coverage areas. Data dashboards also can help to monitor the impacts of shared micromobility services (e.g., travel behavior, environmental impacts, social equity, etc.) and aid in enforcement actions. For example, Ride Report employs a variety of data sharing and public APIs to create a dashboard depicting the bicycle and scooter locations in real time. Translating shared micromobility data feeds into data dashboards can provide public agencies and the public access to curated data on shared services to inform public policy [297], [298].

8.2.5.2 TNC pooling incentives

Transportation Network Companies (TNCs) offer pooled on-demand ride options (e.g., uberPOOL and Lyft Shared Rides) in which users may choose to share a ride with another passenger traveling along a similar path for a reduced fare. However, pooled rides are a relatively small fraction of overall TNC ridership, comprising just 20% and 40% of all Uber and Lyft rides in 2017, respectively [298]. Data on matching rates for pooled rides are scarce, suggesting that the density of pooled ride requests remains insufficient to facilitate a significant increase in vehicle occupancy [30], [96]. In 2017, both major TNC companies launched modified versions of their pooled ride services, called Uber Express POOL and Lyft Shared Ride Saver, which require that passengers walk a short distance to/from their pickup/dropoff location. These services resemble microtransit services, which offer flexible- or fixed-route rides with fixed-schedule or on-demand service in shuttles or vans [297]. Several policy options exist for expanding TNC pooling at the State, regional, and local levels including: 1) SB 1014 (California's

Clean Miles Standard), 2) dedicated pickup and dropoff locations, 2) curb access restrictions and pricing, 3) subsidized pooled trips, and 4) discounts/promotions. Each is explored below.

SB 1014 (2017-18): *California Clean Miles Standard and Incentive Program: zero-emission vehicles (ZEVs)* (hereafter CMS) builds upon the Passenger Charter-party Carriers' Act, which established operational protocols for TNCs governed by the California Public Utilities Commission (CPUC) and grants the California Air Resources Board (CARB) authority to monitor and regulate GHG emissions resulting from this legislation. CMS requires that CARB establish a baseline metric for relative *passenger-mile GHG emissions* from vehicles used on TNC platforms (using data provided by the TNCs) by January 1, 2020—the baseline year is 2018. In addition, by January 1, 2021, CARB must adopt and CPUC must implement annual targets and goals starting in 2023 for GHG emission reductions from every TNC. This policy recognizes the importance of pooling (higher occupancy levels) through its based line metric and GHG target, which also provides credit for active transportation personal miles traveled). Similar to SB 375, CMS requires that TNCs develop (and then execute) GHG emission reductions plans by January 1, 2022 and every two years after.

It is important to note that CARB is currently assuming that pooling activity will recover to 2018 levels by 2023 and increase through 2030, with levels in Los Angeles, San Diego, and San Francisco equivalent to: 1) 35% of all TNC trips are pool requests by 2023 and increases to 50% by 2030, 2) a 70% match rate for pooled trips in 2023 and up to 83% in 2030; and 3) an average occupancy of 1.55 in 2023 and 1.86 by 2030.

CARB, CPUC, and the California Energy Commission are also responsible for aligning state planning efforts and funding programs with CMS goals. CPUC is ordered to:

- Ensure minimal negative impact on low- and moderate-income drivers (social equity);
- Ensure the program complements sustainable land-use objectives;
- Support goals of clean mobility for low- and moderate-income individuals (social equity); and
- Encourage collaboration on investments to support CMS between EV charging companies, investor-owned utilities, fleet owners that provide cars for TNCs, and contracting agencies to provide ZEVs to TNC drivers.

At present, CARB is also formulating CMS credits for TNCs that offer shared micromobility services and additional credits for bicycle infrastructure (see discussion about shared micromobility policy above), as well as supportive partnerships with public transit agencies as part of the Innovative Clean Transit regulation (equal to the credit received by the public transit agency for zero-emission first- and last-mile connectivity for transit riders.

In residential and commercial zones, dedicated pickup and dropoff locations for on-demand rides can aid in aggregating demand for indirect ride services, while providing a mechanism for pricing and/or enforcement of desirable curb access restrictions. In particularly congested conditions that arise frequently in central business districts during peak commute hours, the combination of mileage-based congestion charging with time-dynamic curb access restrictions could offer a promising strategy to manage congestion from on-demand rides while incentivizing pooling. Subsidized pooled rides for travelers that are low-income, unemployed, or have a medical condition/ handicap could greatly increase mobility and accessibility for these groups.

In addition, level of service regulations or incentives analogous to shared micromobility permit programs (see above) could be recommended to ensure a minimum level of travel time reliability for particular geographic regions or user groups. Simple promotions could also provide effective pooling incentives. Offering a discount off of a future ride in return for choosing a pooled ride could be an impactful strategy for reducing VMT during peak or abnormal congestion periods, such as during rush hour or a major event. Travelers can also be incentivized to pool across multiple trips by offering a free ride in return for a number of shared rides. Finally, offering a discount on a public transit fare in return for pooling to a public transit station could be a strategy for increasing public transit ridership through pooled first/last mile connections (Lazarus and Shaheen, 2020, Forthcoming).

8.2.6 Roadway Capacity Expansion Considerations

These strategies will be more effective in reducing VMT if paired with a commitment to no longer program projects that expand highway capacity. Such projects, whether additional lanes on existing highways or entirely new highways, increase the speed of travel, at least initially, thereby reducing the incentive to use other modes. They also encourage more driving, a phenomenon known as “induced travel,” by reducing the time cost of driving thereby encouraging longer trips, more trips, and a shift from modes other than driving. Research shows that a 1% increase in highway capacity within an urbanized area will produce an increase in VMT of about 1%, on average, within five years or so (Handy and Boarnet, 2014). The available research suggests that HOV lanes have the same effect as regular lanes. Although empirical studies of the effect of HOT lanes on VMT are not yet available, theory suggests that any project that reduces travel times (including, for example, interchange improvements) will generate additional VMT. In situations where additional highway capacity does not significantly reduce travel times, as is often the case for projects in rural areas, the induced travel effect is likely to be minimal.

8.2.7 Policy Interaction Considerations

There is considerable uncertainty regarding how certain policy measures might either reinforce or undermine each other, and a detailed assessment of this complex interaction is beyond this study’s scope. However, Table 8.3 below provides the views of the team in a more qualitative way, to identify potential opportunities and issues for further consideration.

One concern is that increases in telecommuting will lead to population decentralization rather than densification. The net effect on VMT would depend on the degree to which reductions in VMT for commute purposes are offset by increases in VMT for non-commute purposes. These trends are hard to predict and will play out over many years, and in ways that policies to encourage densification can continue to address. The following table suggests our judgement on how these several policies might generally interact, mostly in supportive “positive feedback” rather than “negative feedback” types of loops but in ways that are very complex to estimate in advance of policy introduction

Table 8.3. Qualitative Summary of VMT Related Policy Interaction Effects

Policy Area	TOD/ Infill	Active transp.	Transit invest.	Gas tax	VMT fee	Cordon	Parking	Telework	Carpool	Shared micro.	TNC incent.	Transit passes
TOD/Infill	N/A	++	++	+	+	+	+	+/-	+	++	+	+
Active transport	++	N/A	++	+	+	+	+	+/-	+	++	+	++
Transit investment	++	++	N/A	++	++	++	+	-/0	+/0	+	+/-	++
Gas tax increase	+	+	++	N/A	+	+	+	+	+	+	+	+
VMT fee	+	+	++	+	N/A	+	+	+	+	+	+	+
Cordon pricing	+	+	++	+	+	N/A	+	+	+	+	+	+
Parking pricing	+	+	+	+	+	+	N/A	+	+	+	+	+
TDM - telework	+/-	+/-	-/0	+	+	+	+	N/A	-	+	0	0
TDM - carpooling	+	+	+/0	+	+	+	+	-	N/A	+	+	0
Shared micromobility	++	++	+	+	+	+	+	+	+	N/A	+	+
TNC incent./sharing	+	+	+/-	+	+	+	+	0	+	+	N/A	+
Subsidized transit pass	+	++	++	+	+	+	+	0	0	+	+	N/A

Note: "++" denotes a strongly supportive policy interaction; "+" denotes a supportive policy interaction; "0" denotes a neutral policy interaction; "-"denotes an undermining policy interaction; and "- -" denotes a strongly undermining policy interaction.

As shown in Table 8.3, most of the policies tend to be either weakly or strongly reinforcing, suggesting that the policies examined here are expected to be at least additive in their impact, as assumed in the first-order version of this analysis. Policies around telework are expected to have a mixed effect, supporting some strategies but potentially undermining others such as carpooling and strategies around densification and changes to the built environment. Transit investments and active transportation are estimated to have the most positive reinforcing effects, supporting each other as well as several of the other strategies and policy sets in reducing overall per-capita VMT.

8.2.8 VMT Strategy Equity Considerations

Policies and strategies to reduce VMT across the state will substantially impact carbon emissions in the transportation sector. However, efforts to reduce VMT must consider the direct and indirect impacts on low-income, minority, and other vulnerable groups. Mitigating impacts on vulnerable groups will avoid repeating harmful practices of the past and ensure that the benefits and burdens of a low-carbon transportation system are equitably distributed.

Policies to reduce VMT highlighted in this chapter address the built environment, transportation pricing, employer-based transportation demand, shared micromobility, and policies to increase transit use for some groups. These policies carry with them implicit equity concerns that can disproportionately affect vulnerable groups. These equity concerns, as well as some mitigating strategies, are provided in this section.

The built environment directly affects VMT and can serve as an agent to increase health and well-being. Promotion of Transit-Oriented-Development (TOD), active transportation, and robust public investment in transit can reduce carbon emissions. These can also have unintended consequences for vulnerable groups. Specifically, for those in communities that have been marginalized and affected by large-scale transportation infrastructure in the past.

Transit-Oriented-Development increases the appeal for an area, typically attracting younger upwardly-mobile residents. Demand for housing in TOD’s often results in an increase in cost-of-living in the local community. Consequently, low-income households, who rely most on access to public transit, may be out-priced and displaced. Such households may be insulated from the negative impacts of VMT reducing policies if secure housing options are provided, allowing low-income households to remain in or near TOD’s.

Other built-environment policies to reduce VMT include robust efforts that promote active and public transportation. While these policies provide alternative transportation options, vulnerable communities have legitimate concerns over these policies regarding safety. Many vulnerable groups, especially low-income and minority communities, rely on active modes for their transportation needs; often reporting higher than average usage of these modes, largely for work commutes. However, communities report a history of disinvestment that has resulted in a limited network that includes dilapidated signage, unpaved bike lanes, inaccessible sidewalks, and unkempt crosswalks. Lack of infrastructure in these communities has severe safety implications, often resulting in high rates of vehicle collision. Therefore, promoting active transportation in vulnerable communities must be complemented with aggressive infrastructure investments that promote safety measures in those communities.

Equity concerns in public transportation are focused primarily on issues of personal safety. Community stakeholders have consistently voiced their constituents’ concerns regarding the conditions for vulnerable groups while travelling via public transit. The lived experience expressed by these communities depict consistent hardships that include harassment, violence, theft, and racial profiling while using public transit. Such adverse conditions often encourage individuals to acquire personal vehicles as soon as they are financially able to do so, thus undermining the goal of public transit to reduce VMT. Strategies to increase a widespread use of the public transit system must seek to address the adverse societal stressors that discourages the continued use of public transit as the primary source of mobility.

Research has shown that low-income households typically drive more out of necessity and travel longer distances to their destinations. Consequently, any pricing strategies to reduce VMT such as gas tax, road-based fees, cordon zones, HOT lanes and parking fees will disproportionately affect low-income households. While there is a one-size-fits-all approach to address equity in the various pricing structures, community stakeholders have voiced their concerns regarding the process of developing these measures. Community stakeholders understand that the measures being developed represent a public good, however their message for action is to include the voices of residents in the decision-making process early and often. As these pricing structures continue to be implemented in communities across the state, it is recommended that these are complemented with strong community engagement components that allow space for meaningful dialogue and collaboration with community stakeholders.

Transportation-demand-management policies such as incentives from employers to promote teleworking will become more common, especially in the immediate future as a response to the COVID-19 pandemic. As the pandemic has also demonstrated, the opportunity for an individual to work from home is heavily dependent on the employment sector. While those in professional, industry, government, or academic fields have the opportunity to telecommute, a large portion of the population employed in the service industry do not have that option.

Concerns raised about these types of policies are rather an issue of morality, regarding the risk those unable to work from home are taking during the pandemic crisis. Clearly, there are major drawbacks to working from home, but there are also significant benefits that not all individuals have access to. Strategies should be developed to deploy transportation demand policies where the benefits are equitably distributed across communities.

Other demand management policies such as pooling programs have the potential to create significant VMT reductions with minimal equity implications. Pooling for commuting purposes is not unfamiliar to vulnerable populations. In fact, large numbers of low-income households report high rates of car-pooling for commuting purposes; typically non-sponsored through employers, rather by co-workers or relatives. Demand management policies should seek to include sectors that do not typically offer these programs and incentives to encourage more employees to opt-in. By providing safe and effective connectivity to employees, the purchase of personal vehicles may be delayed, further reducing VMT.

The expansion of market services such as shared micro-mobility and transportation network companies can significantly reduce VMT. The equity concerns regarding these services focus on the fact that these must operate in the existing built environment that, in vulnerable communities, is challenged by historical inequities. In addition to the infrastructure challenges, these types of services must also consider the limitations of vulnerable populations such as limited data plans, no connection to a financial institution, and general unfamiliarity with the services. Most importantly, communities have voiced the concerns over venture capital entities seeking to make a profit from their demand for mobility in disadvantaged communities. Policies to address VMT reduction via these market tools should tailor their operations and seek to ensure that their service meets the specific needs of a community.

Transit operational policies such as subsidized passes for low-income groups are gaining traction in large agencies. These policies provide much needed support, especially for groups that spend a large portion of their income on transportation expenses. For these policies, the equity concerns are focused mainly on the sustainability of these programs overtime.

8.3 Conclusion from VMT Reduction Analysis

A complex set of policies across all types of VMT reduction categories is clearly needed to achieve the 15% reduction by 2045 in per-capita VMT in California. Most of the examined strategies and policies across several categories of VMT reduction will be needed to achieve this, with some flexibility in achieving the 15% and perhaps higher goals through implementation of pricing policies. However, achieving any of these ambitious VMT reduction targets will necessarily require improvements in public transit, micromobility, active transportation and other low-carbon modes to provide sensible transportation alternatives and to reduce equity impacts on lower income populations.

9 Fuel Technology and Policy to Support a Carbon-Neutral Transportation System

9.1 Introduction

The methods used to model fuels in this report draw heavily on those used by the CARB Illustrative Compliance Scenario Calculator and the California's Clean Fuel Future study [204]. There are very few projections of fuel availability or cost specific to California that cover years beyond 2030, and many of the technologies that are likely to be critical parts of the fuel portfolio during that time are still under development. In almost every scenario that achieves carbon neutrality by 2045, or even approaches it, battery electric vehicles (BEVs) make up the predominant fraction of the vehicle fleet, which greatly simplifies the challenge of projecting the fuel mix in the later years of this study.

Modeling a transition to zero-carbon transportation by 2045 is quite different than modeling in previous studies, which typically focused on progress over shorter time horizons (e.g., through 2030) or on endpoints with higher emissions (e.g., "80-in-50" studies, which evaluate an 80% reduction in GHG emissions by 2050). This study's focus on complete or near-complete decarbonization imposes a very strict emissions constraint on the final portfolio of solutions and makes the inclusion of any non-zero emission fuels problematic, since any emissions would have to be offset by negative-emission fuels or carbon capture and sequestration (CCS) projects that result in a net reduction of carbon from the atmosphere on a full lifecycle basis.

For the purpose of this analysis, "carbon neutrality" was defined as achieving emissions from the full lifecycle of all fuels of 5 million metric tons (MMT) of CO_2e or less in 2045, excluding the effect of any net-negative CCS projects that are not part of a fuel-production pathway. Net-negative CCS projects are those in which operation of the project sequesters more carbon dioxide, or other GHGs, than they release. Such net-negative CCS projects—e.g., direct-air capture of ambient carbon dioxide for sequestration, or some types of proposed biofuel or bioenergy projects—result in an absolute decrease in atmospheric GHG concentrations. These are in contrast to some other types of CCS projects, where the carbon sequestration reduces lifecycle emissions, but does not completely eliminate them, resulting in a lower, but still positive rate of emissions, e.g., CCS for enhanced oil recovery (EOR) or capture of carbon from flue gases. Within the fuels modeling discussed in this section, net-negative CCS projects create the carbon budget that yields the 5 million tonne endpoint for carbon neutrality, while CCS projects that are not net-negative are reflected in the declining carbon intensities of various fuel pathways (See: Section 9.4.2 for a discussion of CCS).

Within this framework, two separate questions emerged: First, what fuels were capable of contributing to a carbon-neutral fuel portfolio in 2045? Second, what is the role for fuels that are significantly lower-carbon than those they would displace, but not low enough to be a significant contributor to a carbon-neutral portfolio in 2045?

Electricity, which is statutorily required to be generated from non-emitting sources by 2045, clearly applies to both the long-term and near-term challenges, as do fuels produced using electricity as their primary energy source, such as electrolytically-produced hydrogen or synthetic fuels that predominantly use renewable or non-emitting electricity as their source of primary energy. Fuels with a strong potential for cost-effective integration of CCS, such as hydrogen produced from RNG, with the resulting carbon captured and sequestered could also achieve zero or near-zero lifecycle carbon.

While there are other fuels that claim a plausible pathway to lifecycle carbon neutrality, these have not demonstrated a viable pathway to commercial scale production or cost-effectiveness. This report does not exclude the possibility of one or more potential candidate fuels from emerging in years to come but focuses on fuels for which there is ample evidence of their capacity to achieve zero or near-zero emission deployment by 2045.[18] The primary focus of the modeling work discussed throughout this report was to evaluate scenarios that comply with the 2045 carbon neutrality target. Additional incremental reductions using low- but non-zero-carbon fuels were included where they were judged to be cost-effective or when they were needed for compliance with other statutory and/or regulatory requirements, such as with the Low Carbon Fuel Standard (LCFS).

In this section, emissions are discussed on a full lifecycle basis, unless explicitly identified otherwise. This differs from the methodology of the Statewide GHG Inventory, which excludes most upstream emissions. Using lifecycle emission factors ensures an accurate accounting of transportation-related GHGs and excludes solutions that do not achieve real emissions reductions. For example, under the methodology of the GHG inventory and Mandatory Reporting Rule, many biofuels would be considered zero-carbon because the fuel is biogenic in origin and production emissions may have occurred outside the state. The research team, in consultation with multiple stakeholders and independent experts, determined that using lifecycle accounting for the fuels section would close what could otherwise be a loophole that excluded a vast quantity of emissions from being appropriately counted.

The scenarios presented here are not meant to be a comprehensive list of all possible avenues for compliance with the 2045 carbon neutrality target, nor are they meant to be predictive of real-world behavior. These are meant to discuss key milestones, targets, and policies that will define the coming decades of transportation in California and inform the development of policies meant to achieve the state’s long-run goals. They are also intended to help identify areas where additional research, data, or consultation is most needed.

9.2 Scenarios

For all scenarios that are explicitly analyzed in this study, the Tranportation Transitions Model (TTM) was used to estimate vehicle fleet characteristics and activity. The TTM yields approximate fuel consumption broken into several categories: petroleum gasoline; petroleum diesel; liquid gasoline substitutes, including ethanol and drop-

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[18] Note that some forms of renewable natural gas (RNG) are assessed as having a zero or negative carbon intensity under the Low Carbon Fuel Standard (LCFS). This is due largely to the avoided methane credit offered to some RNG production pathways. This credit is set to phase out well before 2045, and extending it could complicate efforts to decarbonize non-transportation sectors. The total potential supply of RNG from pathways that can claim a sufficiently large credit to reach carbon neutrality is a fraction of California’s total transportation demand. Because of these challenges, RNG does not satisfy either criteria of scalability or 2045 carbon neutrality, though it does contribute to the fuel portfolio during intervening years. See Section 9.4.5 for a deeper discussion.

in synthetic gasoline; liquid diesel substitutes, including biodiesel and renewable diesel; electricity; natural gas, including renewable natural gas (RNG); and hydrogen. Based on these rough categories, the fuels model then further disaggregated the fuel portfolio into constituent fuels, applied limits to certain categories of fuel based on expected capacity constraints, and estimated lifecycle greenhouse gas (GHG) emissions based on Carbon Intensity (CI, a measurement of the GHG emissions per unit of fuel energy delivered) values developed by California Air Resources Board (CARB) for the Low Carbon Fuel Standard (LCFS) [299].

Ideally, the fuels model would be fully integrated into the TTM, to allow seamless scenario analysis and rapid evaluation of scenarios against the constraints of each model, however the timeframe limitations of this study did not permit this. Fuel constraints were fed back into the TTM in approximate fashion, by consultation between the research teams, with iteration until the scenario complied with all constraints imposed by either model.

Parameters for the Business-as-Usual (BAU) scenario largely reflect model defaults; see Fuels Appendix 14.3 for more detail on the development and core methodology of that model. The BAU scenario differs from model defaults in the following ways:

- TTM BAU scenario outputs were used to generate the initial fuel trajectories.
- The LCFS target is assumed to continue the current trajectory of 1.25 percentage point increases each year, which yields a 2045 target of 38.75%.
- Refinery investments were assumed to be the maximum amount currently allowed by the LCFS, equal to 10% of the previous year’s deficits. This is due to the persistence of gasoline as the dominant transportation fuel, which was assumed to support more investments in decarbonizing refineries.
- The persistence of gasoline as the dominant fuel was assumed to also provide a greater incentive for the deployment of lower-carbon ethanol production capacity to support LCFS compliance. Cellulosic ethanol consumption was assumed to rise to a maximum of 1 billion gallons/year by 2044 and sugar ethanol (at least part of which would likely be produced domestically) was assumed to grow to 300 million gpy.

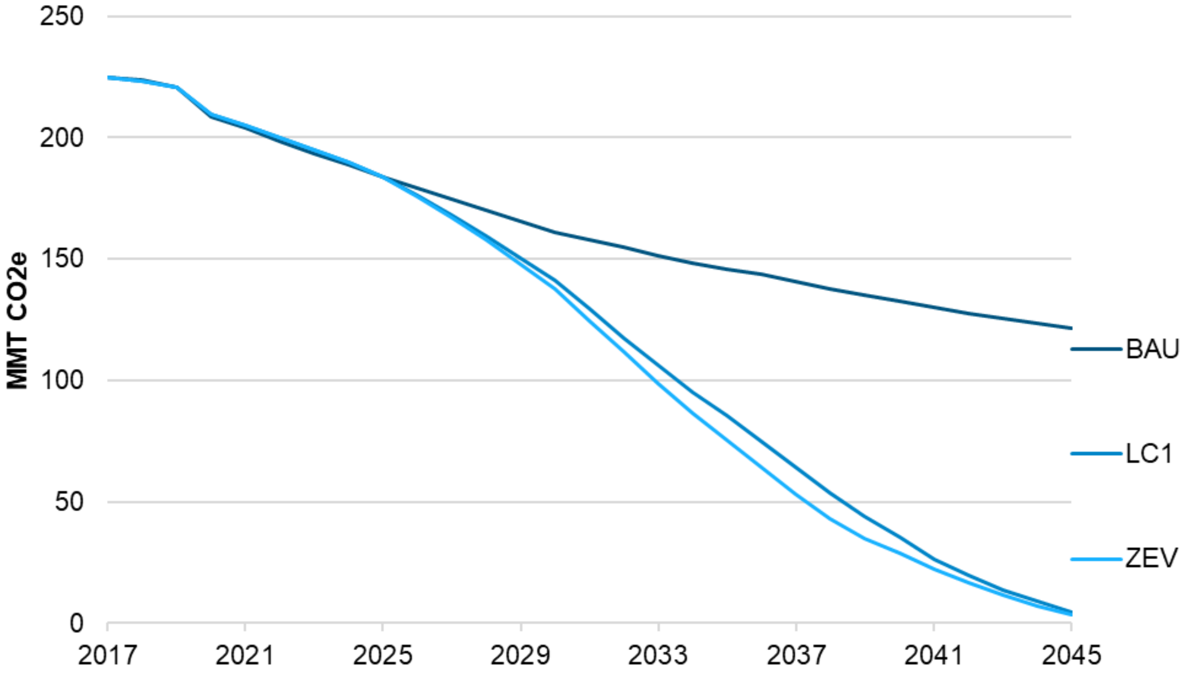

Figure 9.1. Lifecycle GHG emissions from fuels each year in scenarios analysis

The BAU scenario results in a 42% reduction in lifecycle GHG emissions from the production and consumption of transportation fuels Figure 9.1, excluding net-negative CCS. Total consumption of gasoline and gasoline substitutes declines through the mid-2030s due to improved vehicle efficiency, modest displacement by electric vehicles (EVs), and the expansion of the ethanol blend wall in 2030. After 2035, total fuel consumption levels out, as continued efficiency improvements and displacement by EVs are approximately matched by growth in travel demand, though the emergence of some drop-in gasoline substitutes modestly reduces demand for petroleum gasoline. In total, petroleum gasoline consumption drops by about half, to just over 9 billion gasoline gallon equivalents (gge). Diesel consumption continues its downward trend longer than gasoline (Figure 9.2), as improved fuel efficiency and modest growth in electricity and renewable diesel more than counteract increased travel, with petroleum diesel consumption by just under half, to approximately 1.5 billion gge.

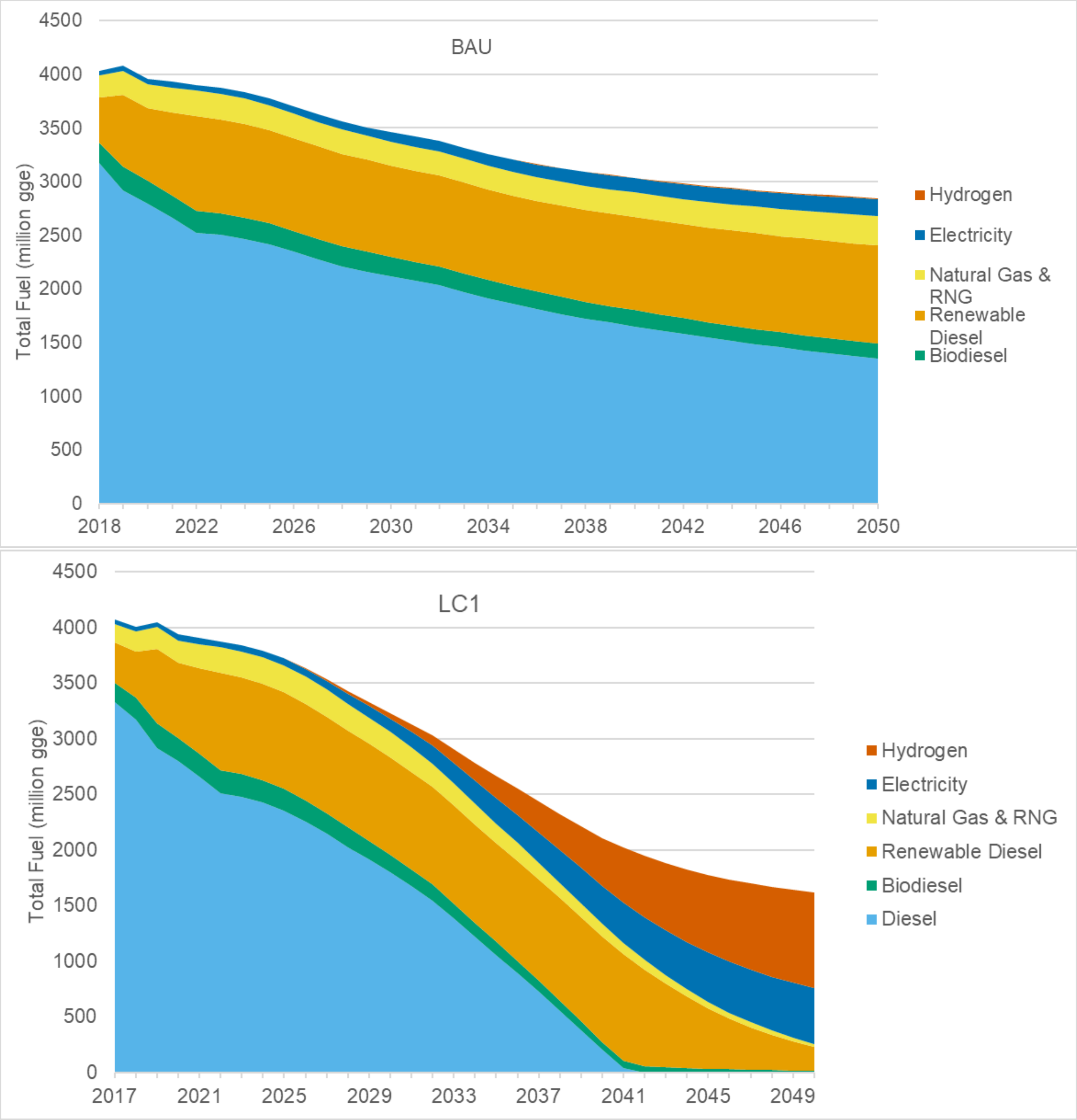

Figure 9.2. Diesel Pool transition in the BAU and LC1 scenarios to 2050

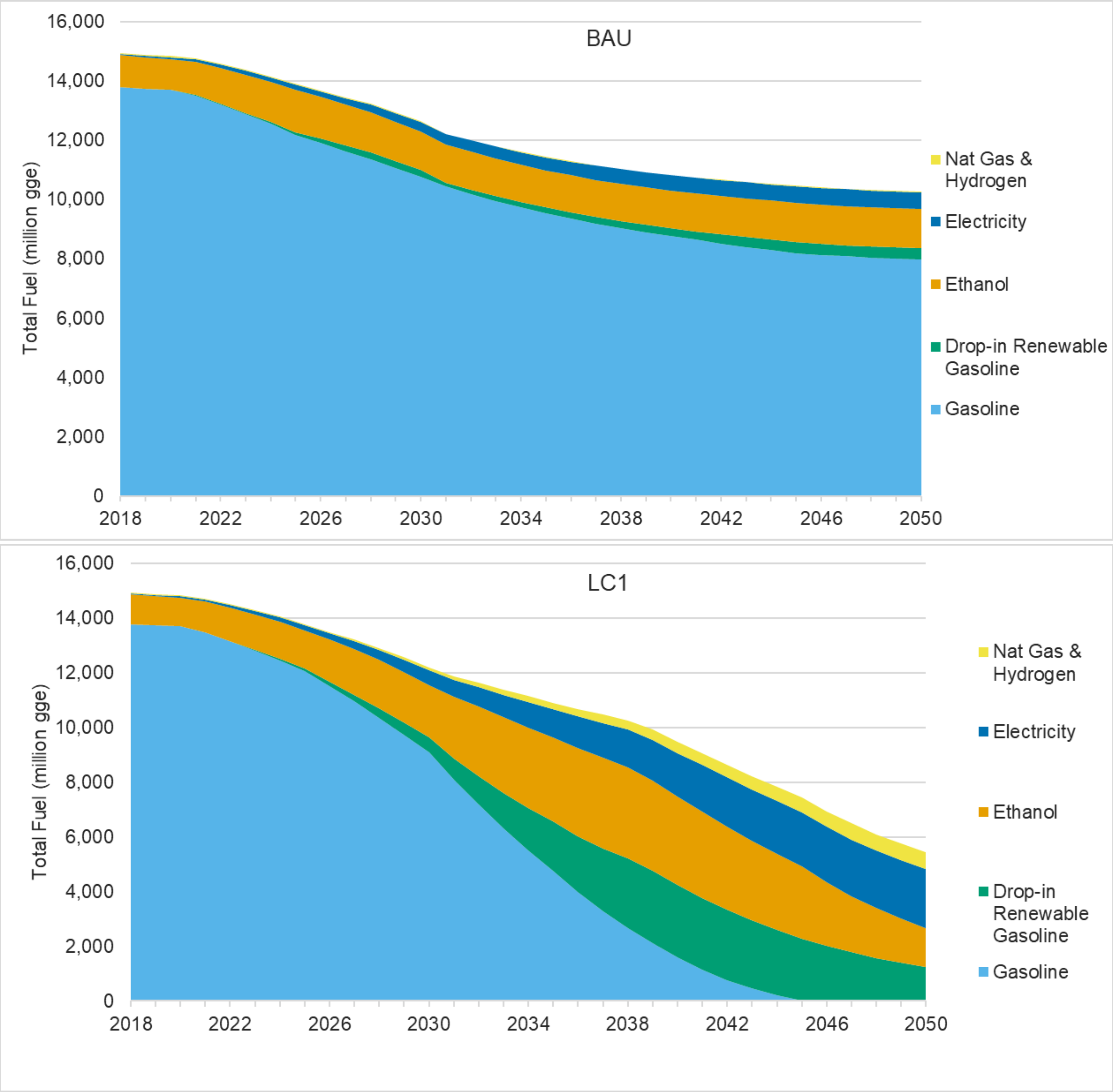

Figure 9.3. Gasoline pool transition in the BAU and LC1 scenarios

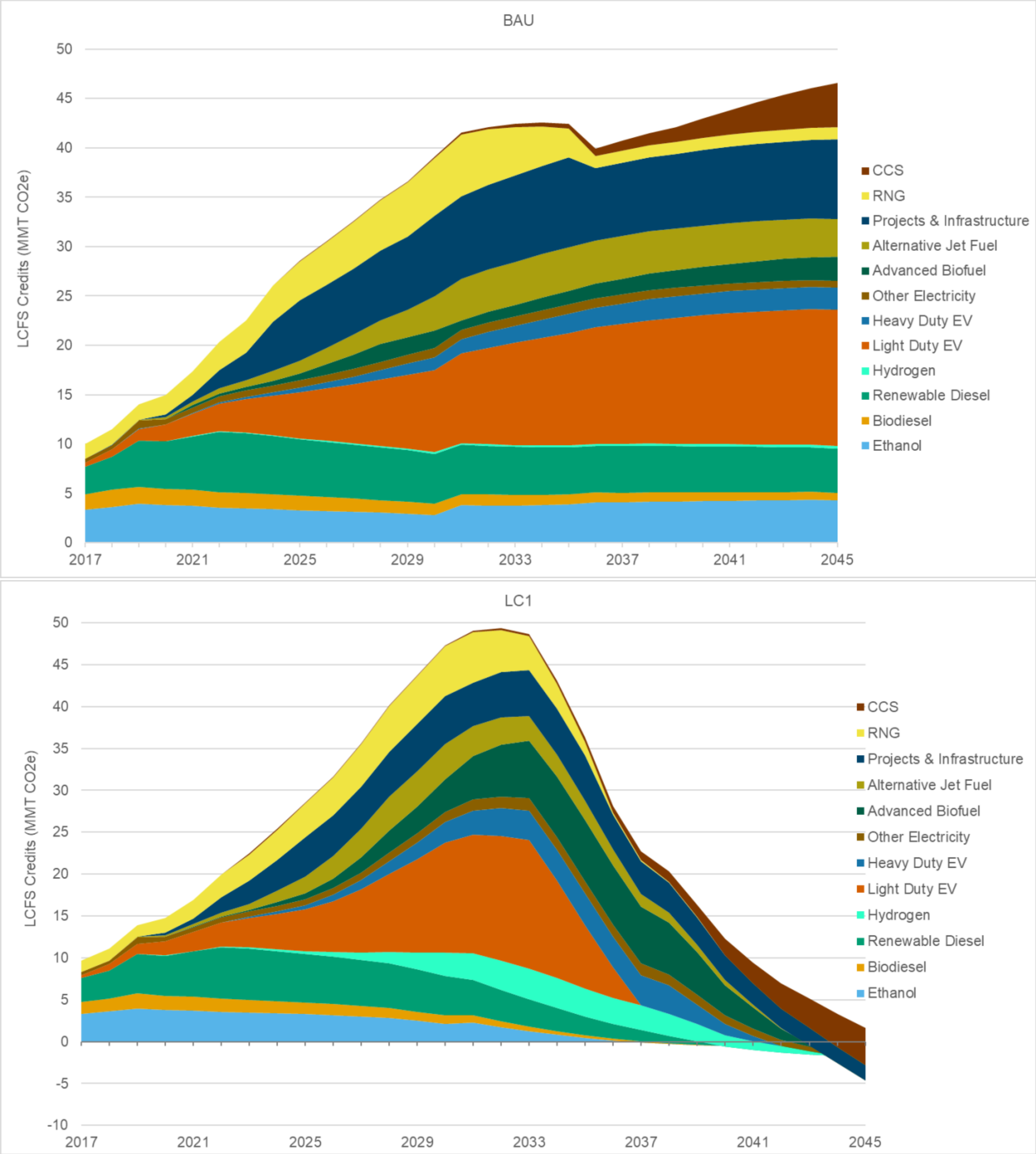

Figure 9.4. LCFS credit generation in the BAU and LC1 scenarios

Compliance with the LCFS, even on a relatively conservative trajectory compared to scenarios that approach or achieve carbon neutrality by 2045, is a challenge in the later years of the program. EVs, despite conservative growth assumptions in the BAU scenario, represent the largest source of compliance credit by 2029. Combined with the expanded ethanol blend wall and incremental reductions in ethanol carbon intensity, the BAU scenario produces robust LCFS credit surpluses through 2035, despite the phase-down of the avoided methane credit for some RNG projects. After 2035, however, aggregate carbon intensity manages to just keep pace with increased LCFS targets, leading to a balance between LCFS credit and deficit generation. Over-compliance with the LCFS prior to 2035 resulted in the accumulation of around 39 million LCFS credits, roughly equal to one year's total compliance obligation for the 2035-2045 period. It should be noted however, that after 2045 the heavy dependence on gasoline leads to persistent deficits that, if unchecked, could deplete the bank by the early 2050s.

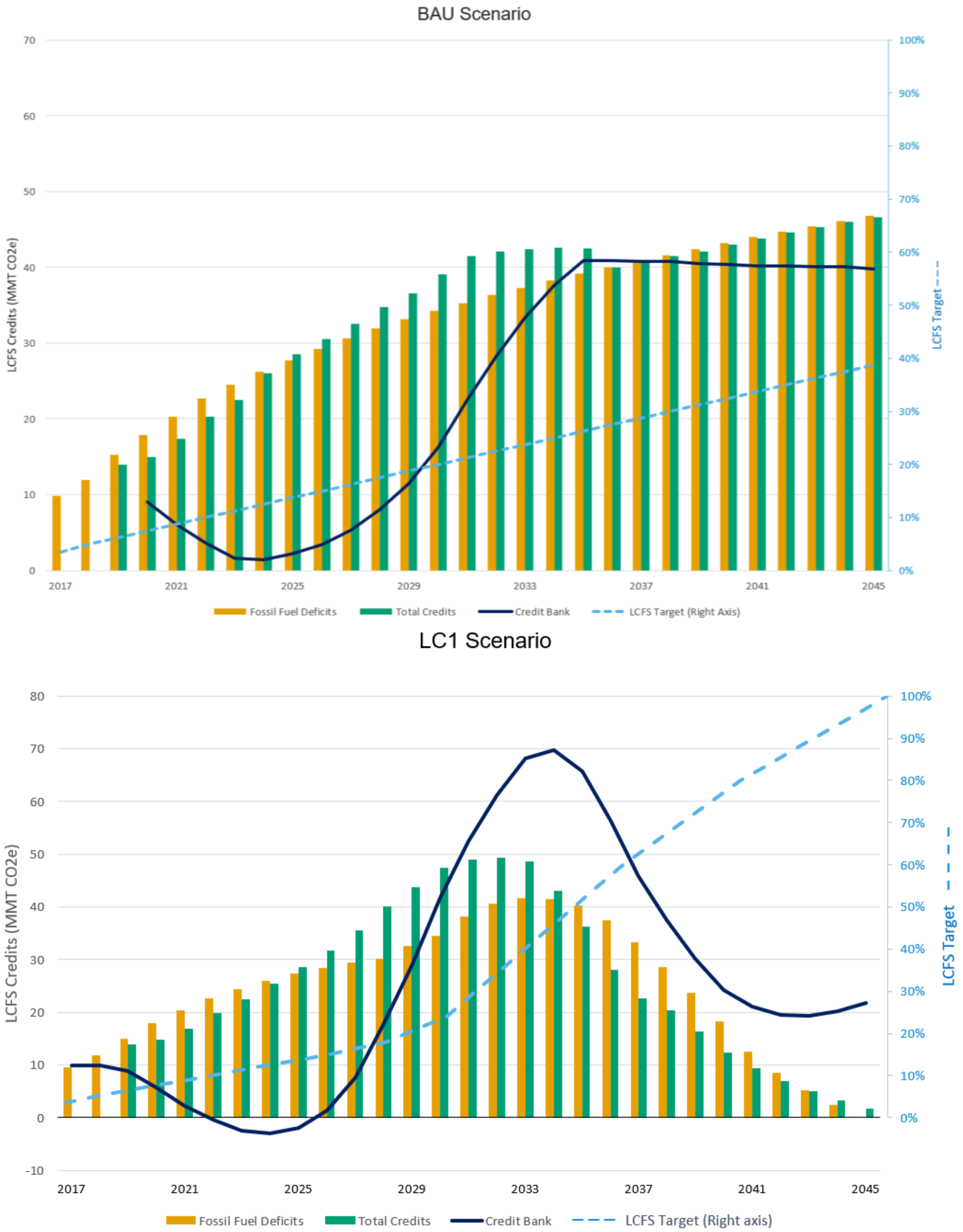

Figure 9.5. LCFS credits, deficits, banked credit balance, and LCFS target in the BAU (*top*) and LC1 (*bottom*) scenarios

9.3 Implications of this Study for California's Fuel Technology and Policy

9.3.1 The Low Carbon Fuel Standard (LCFS)

California's LCFS has guided the state's transition to lower-carbon transportation fuels since its implementation in 2011, and it is well-positioned to continue its role as the state addresses more ambitious decarbonization targets. The LCFS supports the deployment of advanced, very-low-carbon technologies while also providing valuable incentives for the large-scale deployment of currently available alternative fuels. Achieving carbon neutrality will require a significant acceleration of the LCFS target trajectory, primarily after 2030, and will move the LCFS into a new and uncharted operational landscape. This study highlights several key policy implications, which follow.

9.3.1.1 The LCFS Works Best with Long Time Horizons

The LCFS went through a major rulemaking process in 2018, during which it was extended to 2030 with a 20% CI reduction target. During this process, new provisions for ZEV infrastructure, vehicle rebates, and for CCS, were added, along with operational improvements and a third-party verification protocol. A revised cost containment mechanism was added in a smaller rulemaking in 2019. The modeling conducted in this study identified no gaps or flaws in the LCFS that require immediate action, however there are several opportunities in the near term to improve the LCFS' ability to support the long-term transition to alternative fuels.

Transformational changes to the transportation system are quite slow; vehicles often have useful lifespans of around 20 years, and it can take 3–5 years to develop a commercial-scale fuel production facility from concept to commissioning. The long lead times required make it imperative that the State set clear targets a decade or more in the future and demonstrate the regulatory resolve to ensure that they are achieved.

Challenges that emerged in the low carbon fuels space between 2015 and 2019 demonstrate the consequences of not setting targets sufficiently far in advance. Prior to its 2018 extension, the post-2020 statutory authority for the LCFS was viewed as unclear due to political and legal uncertainty. Without certainty that the market for low carbon fuels would enjoy the critical support offered by the LCFS, the pipeline of fuel projects in development slowed dramatically, until the uncertainty was resolved by the passage of SB 32 in 2016, and the adoption of 2030 LCFS targets, which occurred in 2018. This uncertainty almost certainly contributed to the development of comparatively few low carbon fuel projects in the late 2010s, and a tightening long-term supply outlook.

The literature review associated with this report did not identify any studies that directly address the question of how much lead time is enough, though the example of the LCFS in the late 2010s suggests that less than 5 years is insufficient, and longer is preferable to project developers. These developers need enough time not only to develop and execute their plans but also to enjoy the support of the LCFS long enough to recoup their investment. Given that California is about to embark on its next scoping plan process, and any LCFS rulemakings to amend or update the program would likely follow afterwards, a significant package of amendments may not take effect until 2023 or 2024, at which point the lack of a target beyond 2030 could lead to another lull in alternative fuel project development. **Adopting a 2035 target** at the next rulemaking would ensure that prospective project developers could plan on LCFS support over a sufficiently long time-horizon to support continued growth.

The year 2035 is critical for California transportation policy. Along most decarbonization trajectories capable of meeting the 2045 carbon neutrality target, petroleum fuels will supply less than half of total transportation energy starting no later than 2035. This is not only an important symbolic milestone, but it also indicates that the LCFS may be entering a new phase of action (See: Section 9.4.3). Better modeling tools and more data about alternative fuel vehicles and supply systems are needed before a 2040 or subsequent LCFS target can be considered with adequate information.

9.3.1.2 Reevaluating the 2030 CI Target

All of the decarbonization trajectories described in this study include significant policy actions to increase the adoption of ZEVs, particularly battery electric vehicles (BEVs) in the near term. The central low-carbon (LC1) scenario achieves the state's 5 million ZEV 2030 target, while the ZEV scenario exceeds it. The following factors have contributed to a more robust outlook for growth of LCFS credit supply than what was anticipated when the last in-depth credit supply projections were developed: depressed gasoline demand due to COVID-19, the rapid deployment of EVs, robust growth in renewable diesel, rapid adoption of infrastructure capacity and refinery improvement provisions, and continued incremental improvements in ethanol CI. The resulting increase in credit supply couples with the expected effect of additional ZEV policies to yield a rapidly rising credit bank in the late 2020s and early 2030s, peaking at nearly 70 million credits, or 175% of total yearly LCFS compliance obligation, in 2034. This behavior is a continuation of what was predicted by most scenarios modeled in the *California's Clean Fuel Future* report, as well as several in the Illustrative Compliance Scenario Calculator [204], [300]. The fuels modeling conducted in this study was not as granular as either, however it generally echoes the finding that there is a significant likelihood of a large credit bank accumulating in the late 2020s if the state meets, or even approaches, ZEV deployment targets. While a large credit bank is not a problem in and of itself, it may represent a lost opportunity for California to better position itself to rapidly decarbonize in the subsequent decade.

Two key dynamics underpin this conclusion. First, a large credit bank will tend to exert downward pressure on LCFS credit prices, which reduces the financial incentive available to fuel project developers seeking to enter the California market. This would be compounded by uncertainty regarding the status of the LCFS, or if future targets are not set sufficiently far ahead to give assurance of a long-term incentive for low carbon fuel production. Second, California will need to very rapidly decarbonize in the 15 years after 2030 to achieve the target set by Executive Order B-55-18. Transportation fuels in California must go from the 2030 level of carbon intensity, which is 80% of the level they were at in 2010, to essentially zero. Additional progress prior to 2030 reduces the magnitude and pace of the transition required thereafter.

Given the long lead times needed to enact significant changes in the transportation system, an increase of a few percentage points is likely the most that could be feasibly accomplished by 2030, so long as it is enacted as soon as possible to give fuel providers time to adjust to the new target. The ZEV deployment trajectories modeled in this study that achieve the 2045 target are more rapid than those modeled in most of the scenarios considered during the 2018 LCFS rulemaking, which led to the adoption of the current 20% target in 2030. As the modeling presented in this report demonstrates, meeting the 2045 carbon neutrality target will require a much more ambitious, though still feasible, deployment trajectory for ZEVs, resulting in significantly more on the road by 2030. The expected 2030 deployment under a scenario that complies with the 2045 target approximately reflects the level of deployment modeled in the *High Performance* and *High ZEV* scenarios in the *California's Clean Fuel Future* report.

Table 9.1. Total On-Road Electricity Consumption in million gge, 2025 and 2030, in this study and other comparable models.

Source	Scenario	2025	2030
Illustrative Compliance Scenario Calculator	High ZEV	138	338
	Low ZEV	105	183
California's Clean Fuel Future	Steady Progress	205	516
	High Performance	227	588
	High ZEV	257	670
TTM (this study)	Decarbonization (LC1)	195	587
	High-ZEV	195	660

The LC1 scenario in this study also largely agrees with the *High Performance* scenario regarding expected levels of other alternative fuel deployment. The *High Performance* scenario would enable California to meet a 26% LCFS target in 2030 and have a growing credit bank at that time. Given the strong agreement between scenarios that achieve the 2045 carbon neutrality target and the more ambitious scenarios evaluated in previous modeling studies, **CARB should consider raising the 2030 LCFS target** at the next opportunity, to ease the challenge of post-2030 compliance and support a consistent LCFS credit price as an effective incentive for the deployment of low carbon fuels. The Low Carbon (LC1) and High ZEV scenarios discussed in this report assumed a 25% LCFS target in 2030 and still resulted in over-compliance with the target of over 12 and 14 million credits in 2030 alone, which represented overcompliance with the LCFS obligation by 37% and 42%, respectively.

9.4 Key Policies

9.4.1 Developing Low Carbon Liquid Fuel Supply

Given that there is a clear need for drop-in gasoline substitutes to reduce the carbon emissions from existing vehicles (See: 9.4.3, below), California will likely need to provide policy support to bring sufficient quantities of fuel to market. This policy should align with the LCFS in both principal, and execution in order to reduce the risk of inefficiencies through conflicting policy signals. The LCFS does not, by itself, guarantee a sufficient supply of very low-carbon liquid fuels because compliance is assessed on a year-to-year basis and the market mechanism is designed to offer obligated parties the flexibility to find the lowest-cost option. Even though there is a long-term need to deploy very low carbon liquid fuels, obligated parties may be able to comply at lower cost by blending large quantities of fuels that are only slightly lower-carbon than a given year's target or by acquiring credits from EV charging providers. These are valuable outcomes insofar as they reduce emissions, but they may not contribute towards attainment of the 2045 carbon neutrality goal or may even compromise that effort by creating stranded-asset investments in technology or infrastructure with only a limited window of utility while California rapidly decarbonizes.

Policies to support the development of very low carbon liquid fuels should draw from the lessons learned during the decade of experience the state has with the LCFS. Most notably, rather than trying to anticipate technological outcomes or predict “winning” fuel pathways, CARB and other policy agencies should specify the desired performance targets and let producers and the market determine the optimal compliance strategy. There are a number of potential specifications for a compliant fuel, including but not limited to the following:

- Compatible with existing spark-ignition engines, without voiding the warranty or compromising performance.
- Lifecycle carbon intensity below a certain threshold, e.g., 25 g CO_2e/MJ on a well-to-wheels basis.
- Plausible capacity to reduce carbon intensity to meet long-term decarbonization targets, e.g., 5 g CO_2e/MJ or less by 2045.
- Does not significantly increase the emissions of criteria pollutants, toxic air contaminants, or any other pollutant.
- Meets strict sustainability criteria, with minimal indirect land use change impacts.
- Does not interfere with other sectors’ ability to meet decarbonization targets.

Policies to develop supplies of fuels capable of meeting these targets could take any of the following forms, or a combination thereof:

9.4.1.1 Mandated blending levels that complement LCFS requirements.

To develop a supply of fuels which will meet long-term needs, the state could require that an increasing amount of very low-carbon fuels be deployed each year, to stimulate the investments necessary to build production capacity. This approach was unsuccessfully attempted in the Legislature in 2014 through AB 1992 (Quirk), and a smaller program limited to fuels purchased by state fleets was passed under AB 692 (Quirk) the following year [301], [302]. The advantage of the mandated blending level is that it is a relatively simple and self-contained approach to developing the necessary fuel production capacity, though it could result in increased fuel prices, as producers pass the cost of these very-low-carbon fuels through to consumers.

9.4.1.2 Creation of “Very-Low-Carbon” LCFS credits

The LCFS offers an option for implementation of policies targeting very-low-carbon gasoline substitutes. To do this, CARB would develop a set of criteria by which a fuel would be classified as a “Very-Low-Carbon” fuel; the credits generated by that fuel would then carry a special designation reflecting this. CARB would then require that an increasing percentage of credits submitted for LCFS compliance would need to be “Very-Low-Carbon” credits, in a fashion similar to that of the multiple categories of Renewable Identifications Numbers (RINs) under the Federal Renewable Fuel Standard. This approach has the advantage of building off an existing program and developing a funding stream to support the deployment of these fuels, but it would increase the administrative complexity of the LCFS.

9.4.1.3 Targeted Incentives

The State could simply offer financial incentives for the production of fuels that meet the desired criteria, structured in a variety of ways, such as a volumetric credit, a competitive prize, an advance market commitment, or a contract-for-difference between the cost of very-low-carbon fuels and conventional ones. This approach most parsimoniously applies state authority, but it would require the identification of a funding source to support the desired program.

Additional research is required to better understand and model the operation of these policy concepts, as well as the technologies that could plausibly satisfy the specified requirements. Given the long lead times for the development of commercial-scale fuel production capacity, it is important to implement these programs as soon as possible to ensure that fuel providers have enough time to respond.

9.4.2 The Role of CCS in Decarbonizing Transportation

In a carbon neutral scenario, every ton of carbon emitted would have to be taken up, through natural lands, CCS, or other methods. While a number of carbon sequestration options have been identified, the total amount of potential carbon sequestration available to California is particularly uncertain—more so than other technologies for carbon reduction. Recent work led by Lawrence Livermore National Laboratory evaluated potential carbon removal and sequestration options in California and concluded that there is the potential for 125 million tonnes per year. This number is uncertain, however; 25 million tonnes is attributed to uptake by natural lands, which may be challenging given the disruption to many critical ecosystems due to climate change, drought, and wildfire. A further 84 million tonnes of carbon sequestration is attributed to bioenergy or biofuel production with associated CCS, which results in net negative emissions. While there have been multiple studies that highlight the potential of bioenergy/biofuel with CCS (BECCS) as a carbon drawdown tool, no projects have yet been commercialized, and they will require a massive amount of feedstock, which exposes them to many of the same ecosystem and climate risks facing natural lands uptake, as well as potential indirect land use change (ILUC) effects from feedstock production.

While it is clear that there is a significant amount of CCS potential in California, the many degrees of uncertainty that surround it argue against adopting policy that relies on it as a primary driver of decarbonization. While there will almost certainly be millions of tonnes of carbon uptake and sequestration from these methods by 2045, it is too early to quantitatively predict the likely deployment with any certainty Also, there will be sectors of the economy that lack technological options for deep decarbonization [198], such as some methane emissions from agriculture, natural gas transportation/distribution, or fugitive release of high-GWP gases from industrial or electrical operations. Any carbon budget available in 2045 from uptake or sequestration projects may need to be reserved to cover these sectors.

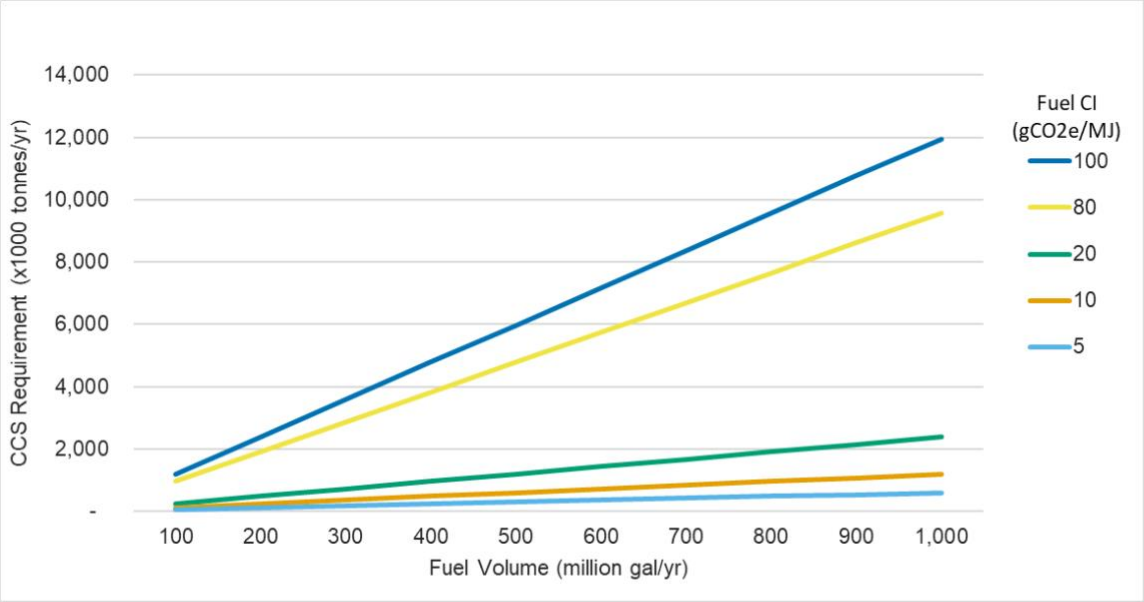

Figure 9.6. CCS required to fully mitigate emissions, by carbon intensity of fuel

Figure 9.6 demonstrates the critical need to ensure that any liquid fuels remaining in the system by 2045 will be extremely low carbon. Two billion gasoline-equivalent gallons per year of fuel with a carbon intensity of 10 g CO_2e/MJ would require 2.4 million metric tons per year of CCS capacity to mitigate its emissions, well within the range identified as feasible by the *Getting to Neutral* report [198], without relying on natural land uptake or bioenergy or biofuel with CCS. At 100 g CO_2e/MJ, the approximate carbon intensity of gasoline or diesel in California, or even 80 g CO_2e/MJ, an approximation of gasoline or diesel in which all production and processing emissions are reduced to zero, the CCS requirement rises rapidly.

9.4.3 Focusing the LCFS on the Most Critical Challenges

The pace of decarbonization needed to achieve the 2045 carbon neutrality goal will require a very fast transition to lower-carbon fuels within the transportation sector, especially electricity. While the overall impacts of this transition are likely to be very beneficial for Californians, success in navigating this transition will bring with it a new set of policy challenges. One that deserves consideration will be ensuring that the LCFS continues to fulfill its role of providing support for emissions-reducing fuels as long as is necessary. Two potential problems may arise as California enters the period of very rapid transition in the 2030s.

First, if the LCFS is to continue to provide critical support for very low carbon fuels, targets will need to rapidly become more stringent. In the 15 years between 2030 and 2045, the fuel pool will need to go from a carbon intensity 20-25% lower than that in 2010 to a carbon intensity of zero, or close enough to zero that natural carbon uptake and CCS projects can account for any remainder. The pace of this change will introduce new challenges into the LCFS market. At present, the relatively gradual increase in LCFS CI targets has allowed sufficient time for the market to adapt to changes and develop new supplies of credit-generating fuels at a brisk but measured pace. The presence of banked credits gives obligated parties a cushion in the event of changes in the fuel market, allowing additional supplies of low carbon fuel to be developed without risking noncompliance with the standard. In the short term, additional renewable diesel or biodiesel could be brought in by tanker, though the amount of such fuel available on short notice to respond to market fluctuations is limited since most production is covered by long-term offtake agreements. Similarly, fuel blenders could acquire lower-carbon sugarcane ethanol instead of corn ethanol, to provide additional credits.

The pace of decarbonization required for California to achieve carbon neutrality by 2045 requires much more rapid progress, equivalent to target increases of several percentage points per year. At this pace, market instabilities may be magnified and banked credits may not provide as much cushion in the event of market instabilities. The higher targets each year could imply growth in the low carbon fuel supply available to California in the hundreds of millions of gallons per year. While there is ample evidence to suggest that the systems supplying California can grow at the required pace, there may be less margin for error and new cost-containment mechanisms may be required, especially since the current one, advancing credits from future residential EV charging, may no longer be available as EVs phase out of the program (See following paragraph). One option would be to allow additional credits generated by CCS unconnected to transportation fuels to enter the market when prices rise above a specified threshold. Alternatively, a return to the previous policy of allowing negative credit balances to be carried forward with interest could also mitigate credit price spikes. Conversely, if the rapid growth in credit generation results in too great a bank of credits, which drives credit prices down too low to effectively support long-term decarbonization, there may need to be a mechanism to further accelerate the targets, or otherwise support stable credit prices.

The second, and more challenging problem is that of aggregate revenue flows through the LCFS market. Throughout its history to date, the LCFS has drawn revenue (through credit purchases) from petroleum fuels, which make up the overwhelming majority of fuel in the state. Each gallon of petroleum pays a relatively small charge, compared to its retail price. The significantly greater volume of petroleum fuels, as compared to lower-carbon alternatives, means that the large pool of fuels supports incentives (through credit sales) to a much smaller pool of alternatives, resulting in a relatively high incentive per unit of fuel delivered.

Table 9.2. Petroleum and alternative fuel volumes in the LC1 scenario.

Year	Fuel Volume (mm gge)	
	Petroleum	Alternative
2020	16,400	2,420
2025	14,580	2,660
2030	11,250	3,320
2035	6,570	4,870
2040	1,850	6,790
2045	–	6,680

If California is to succeed in achieving its climate goals, this relationship will change. All scenarios that are compatible with achieving carbon neutrality in transportation by 2045 see the total energy content of non-petroleum alternative fuels equal that of petroleum fuels in the mid-2030s, and represent well over 80% of total fuel energy by 2040 (Table 9.2). This much smaller volume of petroleum fuels cannot support similarly generous incentives without imposing an onerous charge on each gallon of petroleum sold. While producers of some older, higher-carbon alternative fuels are expected to shift from generating credits to generating deficits—and thereby having to purchase LCFS credits for compliance—it is difficult to foresee enough revenue to continue subsidies to all fuels below the LCFS target in the mid-late 2030s without dropping the subsidy below what is required to support the deployment of advanced, near-zero carbon liquid fuels capable of zero or near-zero emissions at commercial scale.

Given the need to support the development of very-low-carbon fuels, especially liquid gasoline and aviation fuel substitutes with carbon intensities more than 80% lower than their petroleum equivalents, a reorganization of the LCFS will likely be necessary by the mid- to late-2030s. At that point, EVs are anticipated to make up the vast majority of the new vehicle market and be fueled by a rapidly decarbonizing electricity grid, resulting in substantial LCFS credit generation. So long as the grid continues to decarbonize according to targets set by SB 100 and other policies, it is unlikely that EVs, charged by grid electricity will ever generate deficits under the LCFS. The quantity of credits they would generate in the mid to late 2030s, when much of the fleet has shifted away from internal combustion engines could significantly depress the LCFS credit price, muting the incentives needed to support the development of the extremely low-carbon fuels needed to complete the decarbonization of the transportation sector, especially in challenging sectors like aviation, marine, and special-use vocational vehicles.

A potential solution to this problem (and to be clear, this is a problem that is caused by California successfully reducing GHG emissions from transportation by half) would be to reduce or remove EVs capacity to generate credits once they no longer need policy incentives to compete in the market. By the mid-2030s, it is expected that the majority of EVs will be more cost effective than conventional ICEVs, on both a sticker price and total-cost-of-ownership basis. As such, the basic rationale for providing policy support would no longer exist, since they would enjoy a cost advantage in the open market, as well as wide-spread consumer adoption. In addition, electricity has existing statutory obligations for parties to reduce carbon intensity, so once electricity is widely used as a transportation fuel, the LCFS may be superfluous as a measure to encourage further CI reductions. For other fuels that will have established their market competitiveness by 2030, such as ethanol and renewable diesel, the rapidly advancing LCFS CI target will render them deficit generators if they cannot decarbonize at a rapid pace. Electricity, on the other hand, will likely remain a credit generator through 2045, due to the effect of policies unrelated to transportation.

There are several options by which EVs could be withdrawn from the LCFS program. In all cases, it is important to set a clear and consistent plan for doing so well in advance of it actually occurring, in order to allow the market time to adjust. It is also recommended that EVs be phased out gradually, rather than withdrawn all at once, to avoid a sudden reduction in credits while targets continue to increase, and phase outs must not occur until after these vehicles are firmly established as the dominant technology on the market.[19] Additional research

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[19] It is possible, though unlikely, that some other technology, such as hydrogen, algal biofuels, or electrofuels could progress more rapidly than anticipated and exhibit the same behavior as being discussed in the context of EVs, in this section. While EVs have the most likely pathway toward becoming a disruptively prolific source of LCFS credits, other technologies may end up requiring similar treatment.

and modeling are required to evaluate the many possible options for achieving this, but several potential mechanisms may deserve consideration:

9.4.3.1 Phase-Down of Credit Generation

The simplest approach would be to reduce the credit generation per vehicle by a set fraction each year. For example, reducing credit generation by 20% per year until it reached zero in five years.

9.4.3.2 Adjusting the Fuel Displacement Value

When calculating credit generation for some alternative fuels, the LCFS includes an “Energy Displaced” term, to reflect the fact that using these fuels results in the reduction of aggregate petroleum demand by more than the amount of energy consumed by an EV, due to the significantly higher efficiency of electric powertrains. In § 95486.1 (a), the displaced energy is proportional to the energy economy ratio of the vehicle consuming the fuel [303]. This implies an assumption that most or all of the alternative-fueled vehicle activity being credited would have otherwise been done by a petroleum-fueled ICEV. At present, and for the near future, this is approximately true since EVs and other non-ICEVs make up a very small fraction of the overall fleet. As time progresses, however, the assumption that the average EV displaces the activity of an equivalent ICEV would no longer be appropriate, since the California vehicle fleet’s overall composition would shift towards EVs, meaning that for each additional EV, and each additional kWh of electricity charging an EV, the travel being displaced would be increasingly likely to have been provided by another EV. (See: Section 6, Light-Duty Vehicle Electrification for deeper discussion of EV purchase and displacement patterns.)

To reflect this and allow a gradual reduction in EV credits, the energy displaced term (as defined in § 95486.1 (a)(3)) for EVs could be based on the fraction of EVs in the fleet of a given vehicle type. For example, if in 2035, the LDV fleet was 40% EVs, then the displacement term would be multiplied by 60%.

9.4.3.3 Freezing EV CIs at the Model Year of the Vehicle

An alternative method to phase down EV credits gradually would be to specify that EVs would generate LCFS credits using the grid average electricity CI for the vehicle’s model year, to a minimum of zero (that is, they would never generate deficits). This would create a very predictable decline in LCFS credits generated on a per-vehicle basis, with a predictable date for the cessation of credit generation, though this approach does depart from the basic LCFS model of offering financial incentive for real-world emission reduction more than the previous two options.

We stress that the above list is not exhaustive of all possible options, and we make no recommendation about which of the above should be chosen at this point. For the purposes of modeling the Low Carbon (LC1) and High-ZEV scenarios, the phased down approach was selected, because it introduced the least amount of additional complexity into the model, however this does not necessarily imply it is the optimal solution under real-world conditions.

9.4.4 The Future of Advanced Liquid Fuels

Even though ZEVs, especially BEVs, will almost certainly dominate the on-road vehicle market in 2045, modeling of the LC1 and ZEV scenarios show a significant demand for gasoline through 2045. Given the focus on a long-run transition to ZEVs, it is unlikely, though not impossible, that automotive original equipment manufacturers

(OEMs) will make the necessary investments to deploy novel engines that run on advanced fuels other than gasoline, diesel, or equivalents at large scale. This implies that if California wants to achieve the most rapid possible reduction in emissions from the transportation sector, a substantial supply of drop-in substitutes will be needed. California consumes about one-third as much diesel as gasoline, and there are more currently available and expected alternatives. Together, these factors lead to petroleum diesel being phased out around 2040 in the LC1 and High ZEV scenarios, and even lower-carbon diesel alternatives would be largely displaced by electricity, hydrogen, or other zero-emission fuels by 2050, based on projected trends. The greater consumption of gasoline, coupled with fewer proven alternatives mean that drop-in gasoline substitutes will likely be the most critical need in order for California to achieve medium and long term targets. These fuels will have to rapidly scale up while simultaneously reducing carbon intensity to meet the requirements of the ambitions decarbonization trajectory of the late 2030s through 2045 (Figure 9.7). Several plausible options have been demonstrated at small scale and have a plausible pathway to achieving the carbon intensity required to achieve the 2045 target at the scales required.

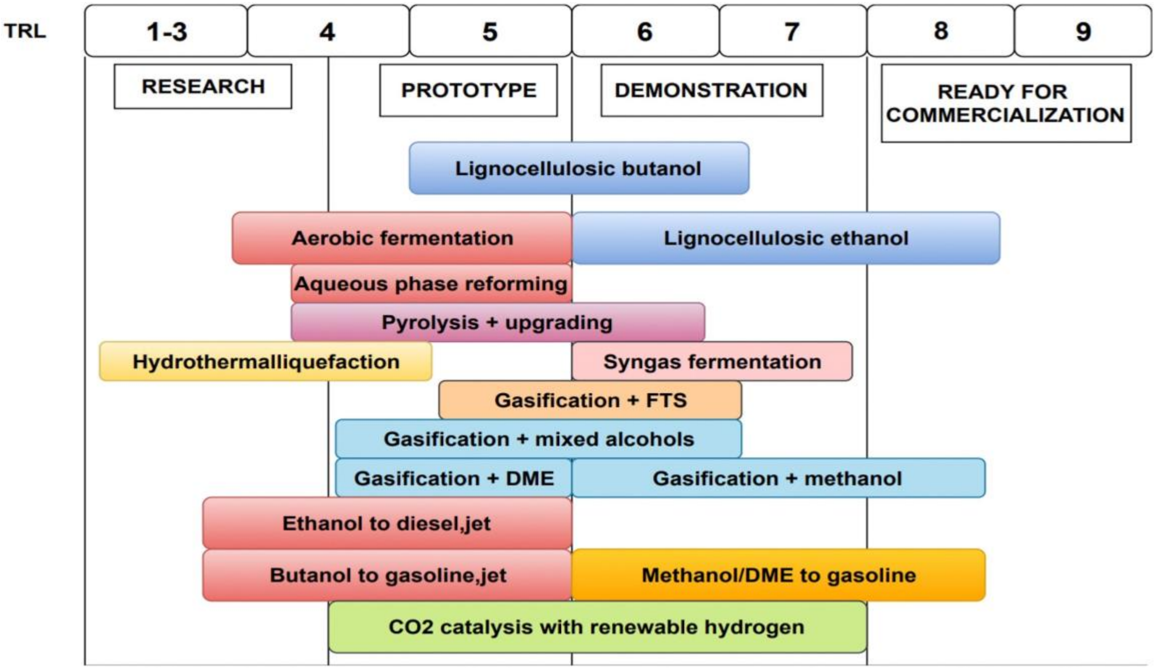

Figure 9.7. Technological readiness assessments for biofuel conversion technologies. Source: (Kargbo, Harris, and Phan 2021), adapted from (E4Tech 2017, 4).

9.4.4.1 Algal Biofuels

Algae are a promising source of biomass for biofuel and bioproduct production, due to high theoretical yields of biomass; the ability to use wastewater, exhaust gases or other wastes as nutrient sources; and the potential for commercial scale deployment across a variety of low-productivity landscapes. Many species of algae naturally produce oils as an internal storage medium for energy, this characteristic can be promoted by selective breeding, careful control of the growth environment, or genetic modification, to maximize the yield of oils. Algal biomass, once produced, can be used as a source of non-fossil oils, carbohydrate biomass, or both, and converted to biofuel through a variety of processes [304]. Industrial-scale production of algae for biofuel purposes has run into several challenges, including contamination by pathogens or less-productive wild strains or microbe, and high energy requirements for separating desirable oils from water or other cellular components [305]. At present, several early commercial algae farming projects have been developed, though most of them seek to produce products for higher-value markets than fuels, such as nutraceuticals, food ingredients, or cosmetics.

9.4.4.2 Cellulosic Biofuels

Cellulosic biofuels utilize the fibrous, inedible parts of plants as feedstock, which allows the use of a wide variety of wastes, residues, or energy crops (e.g., switchgrass, *miscanthus*, or farmed trees) instead of edible agricultural commodities. Because of the higher yields from cellulosic material than from edible starch, protein, or oils from plants and because of less land use competition, cellulosic biofuels have the potential to yield very low-carbon alternatives to petroleum [202]. Cellulosic biofuels have been a topic of significant study for many years; early projections of California's fuel pool under the LCFS predicted that a significant fraction of the fuel pool would consist of cellulosic biofuel by 2020. Several large-scale demonstration projects based on hydrolysis of cellulose into fermentable sugars were initiated in the 2010s, but have since been decommissioned due to challenges with feedstock handling, the production of inhibitory chemicals during processing, lack of supportive policies, and competition from cheaper but higher-carbon food-based biofuels [306]. Still, several promising cellulosic technologies are moving towards large-scale demonstration, though these are predominantly based on thermochemical conversion processes, e.g., pyrolysis and upgrading or gasification and Fischer-Tropsch synthesis, rather than biochemical hydrolysis and fermentation.

A recent study outlined the technical potential for the UK to produce advanced drop-in biofuels to 2030, finding that the most promising technologies were either (i) the better understood ones, e.g., Fischer Tropsch and fast pyrolysis, even though they still face considerable technical and cost challenges, or (ii) newer technologies that could scale quickly (catalytic conversion of cellulosic-based alcohols) due to the ability to extrapolate learnings from first generation biofuel production [307]. A separate assessment of drop-in biofuels pointed to Fischer-Tropsch technologies as most likely to scale soon, despite their higher relative cost, due to longer experience with the underlying technology as well as more practical experience with biomass as a feedstock [208].

9.4.4.3 Electrofuels

In biofuel systems, photosynthesis is used to accomplish the critical step of absorbing carbon dioxide from the atmosphere and stripping the carbon away from oxygen. An alternative pathway has been proposed which replaces the biological role of photosynthetic organisms with technological substitutes, capturing carbon dioxide from ambient air or exhaust gas streams, stripping it of its oxygen molecules, and then using catalytic chemistry to assemble it into a variety of desired products. This tends to be an energy-intensive process [308], however recent advances have reduced the costs and energy demands to the point where large-scale electrofuel production may be possible. If the process is powered by zero-carbon energy sources and uses hydrogen produced via electrolysis using zero-carbon electricity or from renewable sources coupled with CCS, then electrofuels can potentially produce a variety of drop-in fuels at or near zero carbon [309]. Scaling electrofuels to a size capable of meeting California's fuel demand will require significant improvements in efficiency, as well as a substantial amount of zero-carbon electricity production in excess of baseline grid demands, since electrofuels rapidly lose their carbon advantages when powered by carbon-emitting sources of electricity.

9.4.4.4 Biofuels-with-CCS

An alternative approach to producing very low carbon fuels is to capture some or all of the carbon emitted during production and sequester it. The yeasts that ferment sugar into conventional ethanol, for example, produces a stream of very concentrated carbon dioxide during fermentation, which can be captured and sequestered or utilized without needing to be separated from other components of the atmosphere, avoiding the expensive and energy-intensive step of gas separation. Other biofuel production processes yield a sold byproduct, such as biochar or lignin cake, which can be used as soil amendments or simply buried in a landfill to preserve the carbon in solid form. Some of these biofuel-with-CCS pathways may be able to achieve negative net emissions, where the amount of carbon sequestered exceeds that released by non-biogenic sources during production [198].

The above list is not an exhaustive set of all plausible technologies which could yield the necessary liquid fuels. Identifying which of these is most likely to meet the desired cost and emissions and infrastructure compatibility targets is beyond the scope of this study. Given the poor track record of technological prognostication in previous projections of biofuel technologies, maintaining flexibility is important.

9.4.5 The Role of Renewable Natural Gas in a Decarbonized Future

RNG plays a valuable role in a comprehensive decarbonization policy: It yields a valuable energy product, as well as soil amendments, and reduces the uncontrolled emission of methane from decomposing organic matter. Under a lifecycle analysis framework, if the reduction in uncontrolled methane is “additional,” something that would not have happened without the RNG project, then the producer can claim a credit for reducing the amount of methane entering the atmosphere, which further reduces the CI of the resulting RNG. In applications where very high methane release rates are common, such as livestock manure management, the avoided methane credit can be so large that the resulting fuel has a negative carbon intensity—that is, every unit of energy generated by the consumption of that RNG reduces GHG concentrations in the atmosphere. While these projects offer a significant amount of potential GHG reduction, the aggregate supply of economically viable feedstock for RNG production is rather small, most of it from sources that do not qualify for the avoided methane credit, resulting in carbon intensities in the range of 25–40 g CO_2e/MJ on a lifecycle basis. Total U.S. resources compatible with anaerobic digestion are estimated to be between 3 billion and 8 billion gasoline gallon equivalents per year, and perhaps twice that amount if a significant fraction of other biomass resources, like agricultural residue or energy crops, were also dedicated to RNG production [310]. Even at the high end of this possible range, this represents only half of total U.S. diesel consumption.

The limited aggregate potential RNG supply poses a particular challenge, given the wide range of applications that currently depend on natural gas, and for which RNG is one of the few options for decarbonization. At present, natural gas is used as an energy carrier for various end uses—including space and water heating, cooking, electricity generation, hydrogen production, industrial steam generation—and as a feedstock for various chemical processes, such as polymer and ammonia production. As researchers and policy makers gain a better understanding of the technological and policy options for decarbonization, it appears that RNG may play a more valuable role in decarbonizing sectors other than transportation. For applications that use natural gas as an energy carrier, e.g., heat and power generation, renewable electricity likely offers a cost-effective, zero-carbon alternative. However, economic, technical, or infrastructure challenges may necessitate the continued use of natural gas in some energy applications. Even in applications where alternative energy sources could be used, the transition from natural gas to renewable electricity is likely to be gradual, RNG is one of few options for reducing emissions while the transition moves forward. For applications that use the methane molecules that make up natural gas or RNG as a chemical feedstock, there is no alternative analogous to renewable electricity; RNG likely offers the best source of cost-effective, transportable, chemically-available carbon.

While there is still uncertainty regarding long-run decarbonization potentials across many sectors of industry, total industrial consumption of natural gas, including both energy and non-energy uses, exceeds total consumption of diesel by about 16%. Given the relatively limited potential supply of RNG, there may be comparatively little left for transportation uses after industrial demands that lack alternative decarbonization methods are satisfied. At present, there are more attractive policy incentives supporting the use of RNG in transportation—notably the LCFS—than in most stationary applications, which has led producers to generally find the most lucrative market opportunities there. Policy makers may need to re-evaluate the balance of policy incentives to make the most efficient and impactful use of this resource.

In contrast, there are a number of viable alternatives to RNG as a low-carbon transportation fuel. As battery technology has rapidly improved, and renewable diesel has entered the market at a massive scale, there are a number of cost-effective options to reduce emissions from medium- and heavy-duty vehicles. Recent energy transitions studies, such as E3’s recent round of PATHWAYS modeling, indicated that the optimal use of RNG in California’s decarbonization plans would be in stationary applications, rather than in transportation [311].

Weighing the utility or cost-effectiveness of RNG in transportation vs. that in stationary applications is beyond the scope of this study. However, the authors of this study predominantly share the opinion that RNG has greater value, towards California’s long-term goals, in stationary rather than transportation applications. This opinion, however, did not guide the methods employed by this study or the presentation of results. Vehicle and fuel choice decisions were simulated using cost-minimizing functions based on the best available data regarding the costs, performance, and infrastructure requirements for all vehicle types. RNG was included in the portfolio of fuels considered in this study and it played a small but meaningful role in most scenarios. Policies that support alternative fuels, such as the LCFS, were assumed to continue to provide support for RNG as they have historically done and the development of supply trajectories was based on historical performance as well as publicly available data. The results of the model indicated a role for RNG, primarily as a bridge fuel in the medium- and heavy-duty sectors, to incrementally reduce emissions during the broader-scale transition to ZEVs. While there are substantial infrastructure costs associated with large-scale deployment of RNG vehicles, there are some niche applications where its ready availability, or value in meeting near-term air quality goals, justify the investment under current policies. Over the long run, however, the scenarios presented in this report suggest that investments in infrastructure are generally better focused on fuels that have a more certain pathway to zero carbon emissions at large scale and less risk of disrupting decarbonization plans in other sectors.

9.4.6 Impact of Avoided Methane on RNG’s Carbon Intensity

In every scenario presented in this report, there is a noticeable discontinuity in lifecycle GHG emissions around 2035. This is due in part to the anticipation that RNG projects will become ineligible to claim a GHG reduction based on preventing the uncontrolled release of methane (typically referred to in this document as the “avoided methane credit”). At present, RNG projects that reduce methane emissions can claim the GHG reduction benefit from the project as a negative emission associated with their fuel production. This is particularly impactful in the case of RNG production at livestock facilities such as dairies, concentrated animal feeding operations (CAFOs), or swine farms, which have historically allowed manure to decompose in lagoons or open piles, which releases large amounts of methane. Since few regulations or industry procedures require the control of methane from these sources, the reduction is additional to the status quo and credits the resulting fuel for avoiding the methane release as part of best practices for lifecycle analysis.

The sudden increase in lifecycle GHG emissions is because RNG projects, will eventually be unable to claim the avoided methane credit. As part of its Short-Lived Climate Pollutant Strategy, CARB has indicated the possibility of adopting a number of rules requiring the control of major methane sources, particularly livestock facilities. It is anticipated that by the early to mid 2020s, most livestock operations in California will have adopted technologies and procedures to reduce the uncontrolled release of methane. SB 1383 requires that projects active before regulatory requirements take effect can claim the avoided methane credit under the LCFS for 10 years, following a precedent established in the compliance offset protocol for livestock methane reductions. Without a clear understanding of the start date of the RNG projects expected to supply the California market, we assumed that eligible RNG projects would start over the period of time from the present to 2025, after which methane reduction would be required by provisions of the Short-Lived Climate Pollutant Strategy. The avoided methane credit therefore phased down over the period from 2031 to 2035, leaving livestock waste digesters with a low, but no longer negative, carbon intensity of around 20 g CO_2e/MJ, roughly the same level as organic waste digesters that do not receive an avoided methane credit.

While the phase down of the avoided methane credit reduces the supply of LCFS credits in the mid-2030s, this follows both previous regulatory precedent established by CARB and reflects the best practices within the LCA modeling field. The avoided methane credit could be characterized as enabling a fuel project to reduce emissions from agricultural activity and to claim appropriate credit for the reduction. For the fuels sector to claim credit for reducing the methane emissions, the agricultural sector from which it originates must continue to report methane emissions on its greenhouse gas inventories, otherwise the emission reduction would be counted twice, once in fuels and again at the farm. Given the need for California to reduce emissions from all sectors, maintaining the on-paper methane emission in agriculture in order to credit a reduction in transportation would present a challenge for agricultural stakeholders, who would need to find additional sources of reduction to hit their own targets. Without the relatively straightforward and cost-effective option of reducing fugitive methane emissions, agricultural stakeholders may have to adopt more challenging or expensive practices to meet future GHG reduction goals. The deeply negative CIs of RNG with avoided methane may also present a long-term challenge for emissions reduction within the transportation sector, by creating a nominally negative emission source that counteracts emissions from other sources, reducing the effect of the LCFS to support decarbonization of other fuels.

RNG currently provides a valuable pathway for reducing GHG emissions from transportation and will continue to do so for at least the next decade. It should continue to benefit from the incentive offered by the LCFS, even after the avoided methane credit is no longer available. The modeling presented in this study implies that role for RNG in transportation can continue for a time, but additional targeted support for deploying RNG vehicles does not significantly assist the state towards its long-term target of carbon neutrality because RNG does not appear to have a pathway to reach zero emissions once the avoided methane credit is no longer available. There is increasing evidence that the most efficient pathways for decarbonization across all sectors are best supported by using RNG to decarbonize stationary source applications, however that question is beyond the scope of this study.

9.4.7 EV-Grid Considerations

As California transitions to a predominantly electrified transportation sector, emissions reductions from ZEVs are realized by a combination of electric vehicle adoption and a cleaning of the electricity sector. The environmental benefits of electric vehicles are augmented by a shift towards renewable power because the lifecycle impact of charging EVs depends on the source of electricity generation. Fortunately, California already has many aggressive policies supporting a transition to electric vehicles (Zero Emissions Vehicle Program[312], Advanced Clean Trucks Rule [243], Executive Order to reach 5 million ZEVs by 2030 [313], and a ban on sales of new gasoline vehicles by 2035 [3]), and likewise policies that advance the cleanliness and use of renewables in the electricity grid (the Cap-and-Trade Program [314], Renewable Portfolio Standards [315, p. 100]). While these policies are critical to support a sustainable ecosystem in both transportation and electricity sectors, they were developed independently and do not consider an ecosystem in which both electric vehicles and renewable energy are simultaneously growing at a rapid pace. Here we suggest a broad set of policy objectives that consider the interactions of these two systems such that 1) synergies can be effectively enabled between electric vehicles and a renewable energy transition and 2) impacts of a simultaneous transformation can be addressed.

9.4.7.1 Supporting Synergies Between EVs and the Electricity Grid

9.4.7.1.1 Strategic Deployment of Charging Infrastructure

As renewables become increasingly prevalent, it can be beneficial to shift charging load to certain times of the day to prevent curtailment and increase the uptake of solar or wind energy. The use of different types of charging infrastructure (public and workplace chargers versus residential chargers) is heavily correlated with the time of the day [316], [317]. One way to enable shifts towards charging at specific hours of the day is to provide opportunity and access to chargers for drivers. For example, deployment of workplace chargers supports charging behavior that maximizes use of midday solar energy peaks. By targeting specific outcomes for chargers, the infrastructure deployment can be made to better align with emission reduction targets in California.

9.4.7.1.2 Pricing Signals to Incentivize Strategic Charging

Charger availability must also be coupled with pricing signals that lead to shifts in behavior [318]. Strategically pricing the cost of charging based on the time of day can lead to an increase in charging events at desirable times (midday for solar power and during the evening for wind power). Pricing of electric vehicle charging is currently regulated by the California Public Utilities Commission (CPUC). Integrating an emissions or renewables uptake goal into commercial EV charging rate setting would allow utilities and charging service providers the ability to rate recover while simultaneously aligning with sustainability outcomes. While rate recovery calculations would increase in complexity, because providers would need to account for behavioral shifts in response to price changes, this tradeoff allows prices to be explicitly set to meet California’s climate change goals.

9.4.7.1.3 Developing and Standardizing Smart Charging and Vehicle-to-Grid Protocols

One of the benefits of a large-scale adoption of electric vehicles is the massive potential benefit for the electricity grid in the form of vehicle batteries that can double as energy storage for the grid. If California's approximately 25 million light-duty vehicles were to electrify, assuming a 150 to 200-mile range, they would contain about 1,250 GWh of storage capacity, this is a substantial amount of storage considering peak electricity demand load in California is around 50 GW. Well-designed policy can streamline the ability of electric grid operators to take advantage of these storage resources from EVs, allowing them to serve as dispatchable demand, increasing uptake of renewable energy, decreasing curtailment, and reducing the total necessary capacity to meet peak loads.

Regulation is crucial in the standardization of protocols for communication between grid operators and/or utilities with vehicles and drivers. These protocols must span a broad array of new technologies including for the charging infrastructure (what type of information it receives from the grid, how this information is transmitted), the vehicle (interface with the vehicle telematics system), and the linkage between the two (how and what type of information is conveyed). Appropriate regulation may also be able to support the security of vehicle and grid information systems, as well as the privacy of vehicle operators. Such requirements would ensure that all vehicle models, regardless of the automaker, would be able to participate in a vehicle-to-grid system. This would also facilitate aggregators to create systems where participants can elect to allow their vehicles to participate as a grid resource for financial compensation. At large enough volumes, vehicle batteries can potentially mitigate many of the intermittency issues related to high penetration rates of renewable generation as well as enable dispatchable generation capacity to be operated in the most efficient manner possible.

9.4.7.1.4 Public Awareness Campaigns to Guide Charging Behavior

Most vehicles spend the majority of the time parked rather than moving, in theory this translates to an abundance of flexibility for when drivers choose to charge their vehicles. We have outlined several policy mechanisms that could help shift behavior, including an abundance of chargers at the right locations and pricing strategies. However, explicit messaging directly to consumers may also prove to be an effective avenue of shifting charging behavior. Drawing upon the success of the "Flex Your Power" program in California, which led to upwards of a 90% decrease in energy use during peak hours and over a 10% decrease in overall energy consumption in several California regions, an analogous program could be designed for electric vehicles—particularly as the new technology begins to reach a critical mass.

9.4.7.2 Addressing impacts of a simultaneous transition

9.4.7.2.1 Supporting Grid Infrastructure Requirements

Widespread charging infrastructure can lead to challenges for the electricity grid, particularly within the localized distribution infrastructure [319], [320]. For many households, a single Level 2 charger can drastically increase the peak power demand—as these chargers become more widespread, they can stress the capacity of transformers and accelerate degradation. Similarly, for heavy-duty trucks, extreme charging requirements can potentially reach as high as 1 MW for a single charger. This would require a substantial amount of infrastructure to support. At the same time that EVs are becoming increasingly popular, utilities must accelerate upgrades and rollout infrastructure in their respective territories. The California Public Utilities Commission must carefully consider the costs of additional infrastructure due to electric vehicles, as well as how these costs can be recovered.

9.5 Equity

9.5.1 Fuels and Equity: Pricing Impacts

The most common concern related to alternative fuels and policies like the LCFS is the impact on fuel prices. This is especially relevant for lower-income consumers, who often spend a higher fraction of their income on fuel. Appropriately designed policies can minimize, but not entirely eliminate, the impact of transitioning to a carbon-neutral system on fuel prices. The fossil fuel industry has had decades of operational experience and engagement with policy makers, and it has created a system that has harvested most of the cost-minimizing efficiencies possible, though its model fundamentally depends upon exploiting the ability to externalize pollution costs while retaining revenue. The modeling done in this study provides strong evidence that any cost impacts entailed in the transition to a decarbonized transportation system are likely to be massively outweighed by the benefits of the transition: improved public health due to low pollution, economic stimulus from investing in more sustainable technologies, reducing the impacts of climate change (which disproportionately affect lower-income communities), etc.

Additionally, the LCFS has several important cost-minimizing benefits associated with it that are inherent to its fundamental design, whereas most other carbon pricing policies, like the cap-and-trade system or a carbon tax, use revenue from the carbon price itself to counteract potential cost increases to vulnerable communities. First, because retail gasoline and diesel are blends of petroleum and lower-carbon biofuel, each gallon of retail fuel contains a portion that is assessed costs associated with the LCFS deficits it generates, as well as a portion that is provided an incentive associated with the LCFS credits it generates. The ubiquitous nature of biofuel blends like E10 means that the price effects of the LCFS are partially washed out, with the petroleum fraction of a gallon paying into a system that subsidizes the biofuel fraction. This means that the LCFS sends a stronger and more visible price signal to producers than consumers, which mitigates the potential regressive effects.

Second, because the LCFS retains credit revenue within the transportation space, the aggregate effect on transportation fuels is largely cost-neutral. There may be distributional effects that lead to equity concerns, but at the same time, the provision of LCFS credits provides especially valuable benefits to some forms of transportation. Electric buses, for example, receive a per-kWh incentive approximately one third higher than passenger vehicles. In 2020, this provided 20-25 cents per kWh for electricity used in buses, which in some cases covered the entire price of electricity. Policy makers can work to further leverage the operational cost-reducing effects of the LCFS to disadvantaged communities even further. Utilities that generate credits from residential EV charging are obligated to spend half of the revenue they retain from these credits on equity-enhancing projects. One potential option deserving of further study would be to design a set of criteria that would identify a given LCFS credit as being particularly equity-enhancing, then requiring that a certain fraction of credits used to comply with LCFS requirements come from these equity-enhancing sources.

9.5.2 Fuels and Equity: Air Pollution

Another common concern related to fuels policy is the distribution of air pollution impacts. Disadvantaged communities are disproportionately located in highly polluted areas, often near highways or other transit corridors and hubs. At a high level, the displacement of petroleum fuels for lower carbon alternatives is likely to result in a significant improvement in air quality, since lower-carbon alternatives, compared to petroleum, almost universally have lower criteria pollutant and hazardous air pollutant emissions. The benefits of these fuels are not always equitably distributed, geographically or demographically, so careful, spatially-explicit analysis is required to better understand the potential impacts. Few such studies have been conducted to date, in part due to few empirical examples of decarbonized fuel systems to draw from.[20] Another challenge is the lack of accurate data on where alternative fuels, especially diesel substitutes are combusted. The LCFS tracks fuels through distributors or blending terminals (“racks”), but that data is not publicly available. Once the fuels enter the retail market, however, it is difficult to accurately track where they are sold at retail, or where the vehicles that purchase them drive.

Even without these data, however, several outcomes can be inferred from available evidence. One likely outcome is that since disadvantaged communities are disproportionately affected by diesel pollution, and California’s LCFS has shown a pattern of over-compliance in the diesel pool to date, that further expansion of alternative fuels policies supported by the LCFS will likely result in reduced risks from diesel pollution in these communities. The modeling in this study indicated that petroleum diesel was likely to be reduced to zero several years before petroleum gasoline, indicating that it is likely that this behavior will continue. So, it is reasonable to infer significant improvements in air quality in disadvantaged communities from broad decarbonization of the transportation system.

There is also concern that the expansion of alternative fuel production will follow historic patterns of injustice or perpetuate existing ones. Refineries are a major source of air pollutant emissions affecting disadvantaged communities in California; members of these communities have expressed concern that biofuel production may replace petroleum processing at these refineries and allow their pollution to continue. Given that this sort of coprocessing or refinery conversion is relatively new, few empirical studies of the air quality impacts are available. Modeling these systems indicates that adding co-processed bio oils can result in small increases in pollutant emissions from refineries, though generally well below thresholds for significant review under the New Source Performance Standards or National Environmental Standards for Hazardous Air Pollutant provisions of the Clean Air Act [321]. The Bhatt, Zhang and Heath study evaluated only emissions from within the refinery fenceline and did not consider the impact of lower emission fuels on vehicle tailpipe emissions; nor did the study consider whether the reduction in petroleum demand caused by co-processing would reduce the air quality impacts of oil production. Since the feedstocks for biofuels typically have fewer heavy metals, sulfur and other pollutant-increasing components, the risk of increased emissions from coprocessing biofuels in refineries or converting refineries to biofuel production are likely low, but additional research is required to make this determination.

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[20] UC Davis is about to begin a study of the air quality impacts of Oregon’s proposed LCFS changes, which may be the first of its kind to attempt to evaluate the effects of state-wide fuels policy on air quality, at a very granular spatial level.

10 Assessment of Health Impacts

10.1 Introduction

To estimate the potential health benefits from reaching carbon neutrality in the transportation sector by 2045, we relied on two different approaches. First, every 5 years starting in 2025 and until 2045, we used InMAP to estimate changes in concentrations of $PM_{2.5}$ between the BAU and the LC1 trajectories. Second, in 2045 we used the Community Multiscale Air Quality Modeling System software (CMAQ; https://www.epa.gov/cmaq) [322] to calculate changes in concentrations of $PM_{2.5}$, ground-level ozone, and NO_x between the BAU and the LC1 trajectories. For both InMAP and CMAQ air pollutant concentration results, we then relied on BenMAP to estimate changes in selected health outcomes for $PM_{2.5}$ and ground-level ozone (the latter only for the CMAQ analysis). Both approaches are outlined below. We chose this approach because it was too time-consuming to estimate results with CMAQ only.

10.2 Approach 1: InMAP

10.2.1 Overview

InMAP (Intervention Model for Air Pollution) [323] provides an alternative to comprehensive Chemical Transport Models (CTM) for estimating annual average primary and secondary $PM_{2.5}$ concentrations by preprocessing the output of a more comprehensive model (i.e., WRF-Chem) to extract atmospheric properties. In comparison with other reduced-complexity models such as COBRA, InMAP is more spatially detailed and it can use a variable grid that dynamically updates between iterations based on pollutant concentrations and population density. InMAP relies on a steady-state numeric solution to the reaction-advection-diffusion (RAD) equation and annual average input data. It is important to emphasize that InMAP is intended to estimate impacts of marginal emission changes rather than total ambient concentrations.

10.2.2 Input data

InMAP combines various inputs (on-road $PM_{2.5}$ and precursor pollutant emission derived from emission factors, CEPAM emissions from other pollutants), and their distribution in space (Spatial distribution of on-road emissions). They are described in turn.

10.2.2.1 Emission Factors

Emission factors for $PM_{2.5}$, ROG, SO_x, and NO_x were extracted from the EMFAC2017 v1.0.3 emission inventory and obtained by dividing total emissions for each pollutant by total VMT. We estimated an emission factor for each subarea in the state. Sub-areas are defined as the intersection of counties and air basins, which gave us 68 sub-areas covering the state.

The vehicle classes of interest are those corresponding to the vehicle classes modeled in CSTDM as we are estimating emissions using passenger and heavy-duty vehicle miles traveled (VMT) from CSTDM. The vehicle classes of interest include passenger vehicle (LDA, LDT1, LDT2, MDV) and heavy-duty vehicle (LHDT1, LHDT2, MHDT, HHDT). The fuel/vehicle types for which we calculated emission factors include gasoline, diesel, electricity, natural gas (NG), hybrid, and plug-in hybrid. The emission inventory only had NG emissions for 56 of the state's 68 subareas. Given that the variation among subareas was small (see Health appendix), we replaced missing values with the mean value of all other subareas. We used the same approach to estimate missing emission rates for other fuel types.

Table 10.1. Abbreviations

Abbreviation	Meaning
AQ	Air Quality
BAU	Business as usual
BenMAP	Benefits Mapping and Analysis Program
BEVs	Battery Electric Vehicles
CARB	California Air Resource Board
CMAQ	the Community Multiscale Air Quality Modeling System software
CNG	Compressed Natural Gas
COBRA	CO–Benefits Risk Assessment
C-R	Concentration-Response
CSTDM	California Statewide Travel Demand Model
CTM	Chemical Transport Models
DACs	Disadvantaged Communities
EMFAC	Emission Factor Model
EVs	Electric Vehicles
FCEVs	Fuel Cell Electric Vehicles
HEVs	Hybrid Electric Vehicles
HHDT	Heavy heavy-duty trucks
ICE	Internal Combustion Engine
InMAP	Intervention Model for Air Pollution
LC1	Low Carbon
LDA	Light-duty automobiles
LDT1	Light-duty trucks 1
LDT2	Light-duty trucks 2
LHDT1	Light heavy-duty trucks 1
LHDT2	Light heavy-duty trucks 2
LNG	Liquefied Natural gas

Abbreviation	Meaning
MD8H	maximum daily 8-h average concentrations
MDV	Medium-duty vehicles
MHDT	Medium heavy-duty trucks
NAAQS	National Ambient Air Quality Standards
NG	Natural Gas
NH3	Ammonia
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
O3	Ozone
PHEVs	Plug-In Hybrid Electric Vehicles
PM2.5	Particulate matter between 2.5 µm
ppb	Part per billion
RAD	reaction-advection-diffusion
ROG	Reactive Organic Gases
SMOKE	Sparse Matrix Operator Kernel Emissions tool
SoCAB	Southern California Air Basin
SOx	Sulphur Oxides
SPBP	San Pedro Bay Ports
TTM	Transportation Transitions Model
VMT	Vehicle Miles Traveled
VSL	Value of Statistical Life
WRF-Chem	Weather Research and Forecasting (WRF) model coupled with Chemistry

Figure 14.1 to Figure 14.3 (see Health Appendix 14.4) show boxplots for the change in emission rates for heavy-heavy duty trucks (HHDT) for the 68 subareas in the state for each target year. We omitted all other vehicle classes for brevity. We observed similar patterns for them.

In addition, we assumed that electric vehicle $PM_{2.5}$ emissions correspond to tire and brake wear. While electric vehicles have the advantage of regenerative braking (so they do not use their mechanical brakes as often as conventional gasoline or diesel vehicles), their gross weight (partly due to additional batteries) puts additional strain on their tires, which likely increases $PM_{2.5}$ emissions. Since we did not observe variations in PM emission factors between passenger vehicle classes and given that emission rates for heavy-duty vehicles were not available, we adopted uniform $PM_{2.5}$ emission rates for all electric vehicles, irrespective of their class. Figure 14.4 and Figure 14.5 show $PM_{2.5}$ emission rates we assumed for electric vehicles for this analysis.

Of the various pollutants needed to estimate secondary $PM_{2.5}$ concentrations using InMAP, ammonia (NH_3) emissions factors were not available in EMFAC. To obtain plausible values we extracted NH_3 emissions from the CEPAM emissions inventories and divided them by daily VMT for each of our 68 sub-areas. The primary purpose of CEPAM data was to obtain background emissions for the reduced form atmospheric chemistry in InMAP, as explained below.

10.2.2.2 CEPAM Emission Inventory for background emissions

Background emissions of various air pollutants are needed for the atmospheric chemistry used to calculate secondary $PM_{2.5}$ in InMAP. These data were obtained from the California Air Resource Board (CARB) emission projections (CEPAM 2019 SIP v1.01). This vintage was adopted by CARB on June 25, 2020 to support the 70 ppb ozone standard State Implementation Plan. These data are not currently posted on the CARB website, but they are considered public. Annual average emission units are in tons per day, and the projected years include 2020, 2025, 2030, 2035, and 2040.

For our target year, 2045, we applied a simple extrapolation using 2035 and 2040 data as follows: for a given pollutant in one of the 68 county-air basin sub-areas in California, if the projected 2040 emissions are at least as large as the 2035 emissions, we used a linear extrapolation to estimate the 2045 emissions; otherwise, we used a geometric extrapolation by calculating 2045 from 2040 assuming it grew at the same annual rate as between 2035 and 2040. We adopted this simple approach to capture recent trends in emissions, assuming that increases would be moderate (leading to the assumption of a linear increase), and to avoid negative projected values for decreasing emissions (hence our assumption of a geometric function for emission decreases).

To obtain total annual emissions from the CEPAM emissions inventory (which provides annual tons per day averaged over a year), we simply multiplied annual average emissions in tons per day by the number of days in a year.

10.2.2.3 Spatial distribution of on-road emissions

To reflect in a very simple way that secondary $PM_{2.5}$ emissions will likely be higher where primary emissions are higher, we distributed on-road emissions based on census tract VMT. Since CSTDM VMT is only available for four vehicle classes, we used the mapping in Table 10.2 to distribute VMT into eight EMFAC vehicle classes based on the annual VMT inventories available in EMFAC.

Table 10.2. Vehicle Classes Mapping

Vehicle class		
CSTDM	**EMFAC 20007**	**TTM**
Passenger vehicles	Light-duty automobiles (LDA)	Cars
	Light-duty trucks 1 (LDT1)	Trucks
	Light-duty trucks 2 (LDT2)	
	Medium-duty vehicles (MDV)	
Light duty vehicles	Light heavy-duty trucks 1 (LHDT1)	Heavy-duty pickups
	Light heavy-duty trucks 2 (LHDT2)	
Medium duty vehicles	Medium heavy-duty trucks (MHDT)	Medium-duty urban
		Medium-duty vocational
Heavy duty vehicles	Heavy heavy-duty trucks (HHDT)	Long haul
		Short haul
		Heavy-duty vocational

However, VMT also needs to reflect fuel use. Our fuel share data come from the TTM model outputs (annual statewide VMT totals). After splitting VMT into eight EMFAC vehicle classes, we applied the fuel shares from the VMT fuel type percentage by vehicle class (see Figure 14.4 and Figure 14.5 in the health appendix). For the fuel share distribution of each vehicle class, we relied on the mapping shown in Table 10.2 to distribute TTM VMT into the corresponding EMFAC vehicle classes.

Since we only have emission factors for four fuel types (gas, diesel, natural gas, and electric), we aggregated CNG and LNG vehicles into a “natural gas” category. Likewise, we grouped battery electric (BEVs) and fuel cell vehicles (FCEVs) into an “electric vehicles” (EVs) category.

For the fuel efficiency of Hybrid Electric (HEVs), and Plug-In Hybrid Electric vehicles (PHEVs) we relied on data from the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (e.g., constant, mild, and advanced) which reports 22% to 44% fuel efficiency gains dependent on the annual technology baseline and the range of LDV Gasoline Hybrid or plug-in hybrid vehicles. Fuel savings for PHEVs range from 70% to 78% for a 20-mile range, and from 108% to 118% for a 50-mile range. We note that field tests on light-duty hybrid and internal combustion engine vehicles with similar characteristics show similar fuel efficiency. Huang (2019) reported fuel savings of 23% to 49% for HEVs compared to their conventional ICE counterparts. We used the more conservative ATB constant fuel savings for HEVs and PHEVs (44% and 70% respectively).

We also assumed that the emission savings associated with HEVs and PHEVs are equivalent to their fuel savings. Hence, the emissions factors for HEVs (PHEVs) are assumed to be 44% (70%) less than those for their ICE counterparts.

10.2.2.4 Inputs summary

The following shapefiles were generated as inputs to InMAP.

1. **Census Tracts Shapefile**

CSTDM Emission estimates (obtained from: vehicle class VMT*Emission Factor)

- EMFAC's VMT inventory used to distribute CSTDM VMT into eight different vehicle classes;
- The proportion of daily CSTDM VMT on specific census tracts was applied to distribute statewide VMT. For this step we used the outputs of TTM;
- Fuel shares come from the outputs of TTM.

After estimating emissions, we compared statewide emissions to the CARB inventories (CEPAM and EMFAC). Table 10.3 summarizes the difference between our estimation and both inventories. Since CEPAM only includes gasoline and diesel vehicles, we compared the share of emissions associated with gasoline and diesel only. The observed differences are explained by the difference in passenger VMT between EMFAC's VMT inventory and TTM outputs.

Table 10.3. Emissions comparison

	ROG	NO_X	SO_X	$PM_{2.5}$	NH_3
Estimated Emissions	76,709.22	167,207.60	1,808.39	11,250.97	12,761.30
CEPAM	64,127.40	165,837.86	1,572.49	10,305.99	11,610.94
EMFAC	67,726.59	163,369.20	1,643.21	10,606.73	11,610.94
CEPAM Difference	16%	1%	13%	8%	9%
EMFAC Difference	12%	2%	9%	6%	9%

2. **Mobile Emissions Shapefile**

On road emissions from CEPAM mobile inventory replaced for CSTDM emissions out of the mobile emission inventory. Shapefile 2 still includes area sources at the county-air basin level for excluded vehicle classes such as transit buses, and other mobiles sources (e.g., trains, ocean vessels, farm-equipment, etc.)

3. **Stationary Sources Shapefile**

4. **Areawide Sources Shapefile:** Areawide sources at the county-air basin level (e.g., pesticides, asphalt paving, roofing, residential fuel consumption, construction and demolition, cooking, fires, etc.).
5. **Natural Emissions Sources Shapefile:** Natural sources kept at the county-air basin level (e.g., biogenic sources, geogenic sources, and wildfires).

10.2.3 Output

Our InMAP runs were configured to estimate changes in $PM_{2.5}$ concentrations over a constant 4 km x 4 km grid to simplify a comparison of results with CMAQ. The simulation time for each of the Business as Usual (BAU) and Low Carbon (LC1) scenarios was approximately 2.5 hours.

For 2020 emissions (results not shown for brevity), annual average $PM_{2.5}$ concentrations range between 0.00 $\mu g/m^3$ and 14.42 $\mu g/m^3$, with a mean value of 2.75 $\mu g/m^3$. For target years 2025, 2030, 2035, 2040, and 2045 we focused on the difference in ground-level $PM_{2.5}$ concentrations in $\mu g/m^3$ between the BAU scenario which serves as a baseline for comparison against LC1 trajectory concentrations. As expected, for 2025, the difference in $PM_{2.5}$ concentrations is minimum, ranging from 0 to 0.04 $\mu g/m^3$ (0% - 0.63% reduction), with a mean value of 0.03 $\mu g/m^3$ (0.08% reduction in comparison to 2025 BAU). Similarly, reductions in $PM_{2.5}$ concentrations are below 3.10% for 2030. For 2030, we observed some minor $PM_{2.5}$ increases (of less than 0.001 $\mu g/m^3$) on the Great Basin Valleys. While this inverse relationship with precursor emissions is not expected, the very minor increase could be a result of the complex chemical pathways associated with $PM_{2.5}$ formation in the atmosphere including interactions between nitrate-based PM and secondary organic aerosols. It is also important to consider that 1) the magnitude of the increase is very small and 2) occurs in a sparsely populated area. After 2035, the difference in $PM_{2.5}$ concentrations ranges from 0 to 0.48 $\mu g/m^3$ (0.02% - 7.97% reduction), with a mean value of 0.03 $\mu g/m^3$ (0.93 % reduction in comparison to 2035 BAU). Reductions for 2040 are close to double the reductions of 2035, ranging from 0.00 to 0.84 $\mu g/m^3$ (0% - 14.27% reduction). Finally, by 2045, the difference in $PM_{2.5}$ concentrations range from 0.00 to 1.04 $\mu g/m^3$ (0% - 18.27% reduction).

Results (see Figure 10.1 to Figure 10.5) show, as expected that the greatest reductions happen in highly populated regions within the South Coast Air Basin and the San Joaquin Valley Air Basin.

Figure 10.6 shows changes in annual average $PM_{2.5}$ concentrations resulting from 2045 BAU vs LC1 emission changes as estimated by A: CMAQ, and B: InMAP. Both use a 4 km x 4 km resolution to minimize errors for interpolations that would otherwise be needed to compare results.

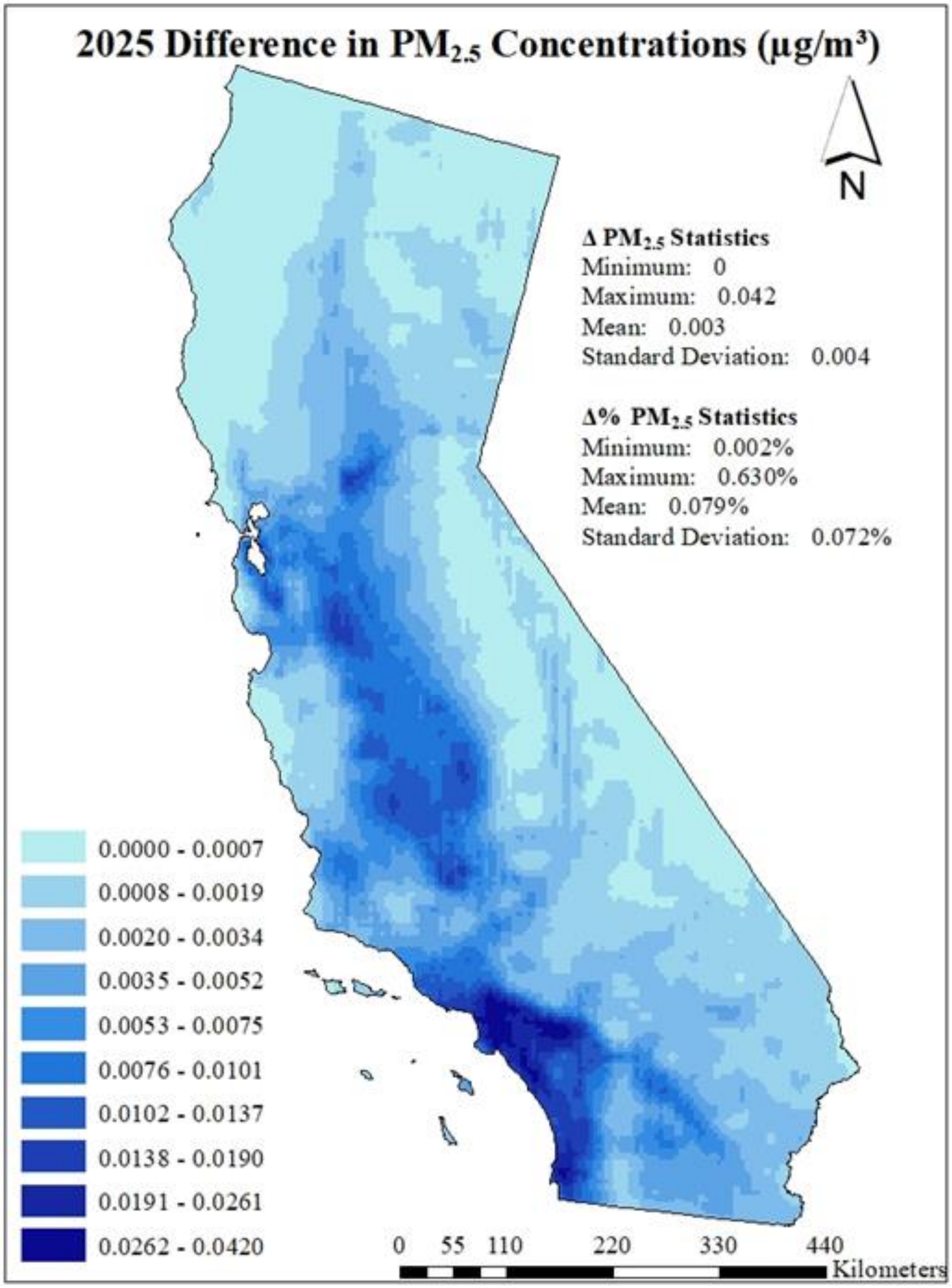


Figure 10.1. 2025 BAU and LC1 Difference in PM2.5 Concentrations

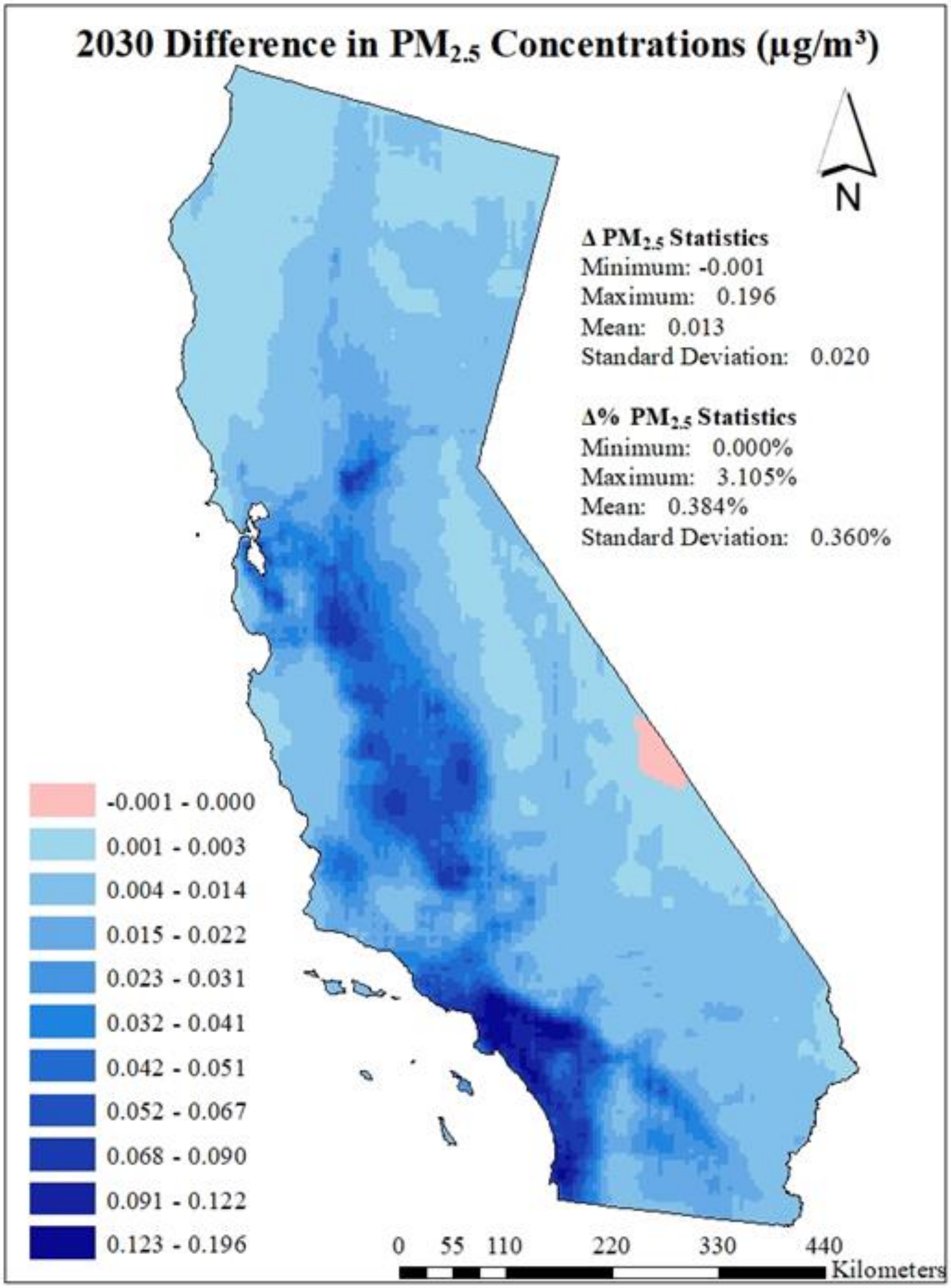


Figure 10.2. 2030 BAU and LC1 Difference in PM$_{2.5}$ Concentrations

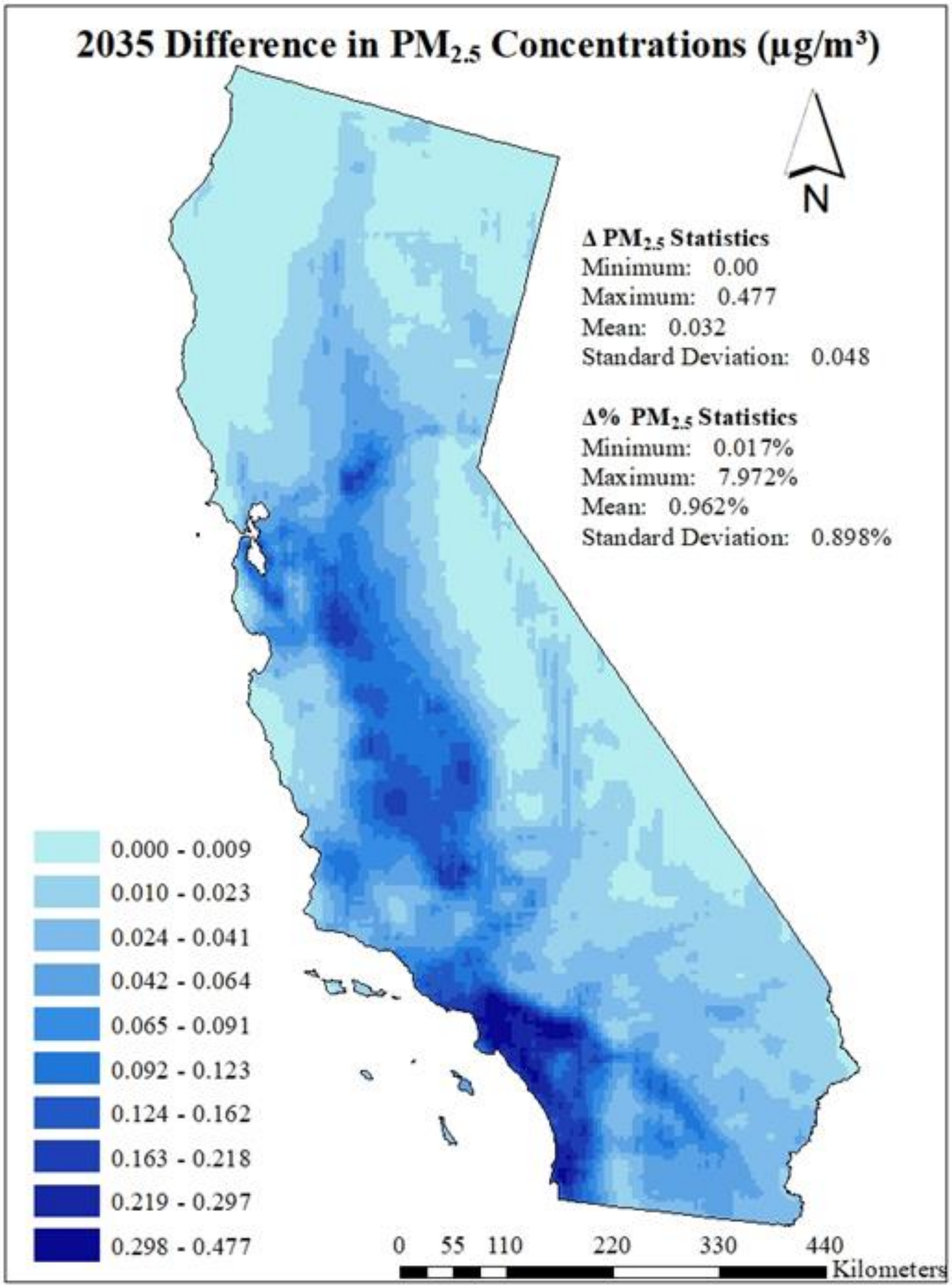


Figure 10.3. 2035 BAU and LC1 Difference in PM2.5 Concentrations

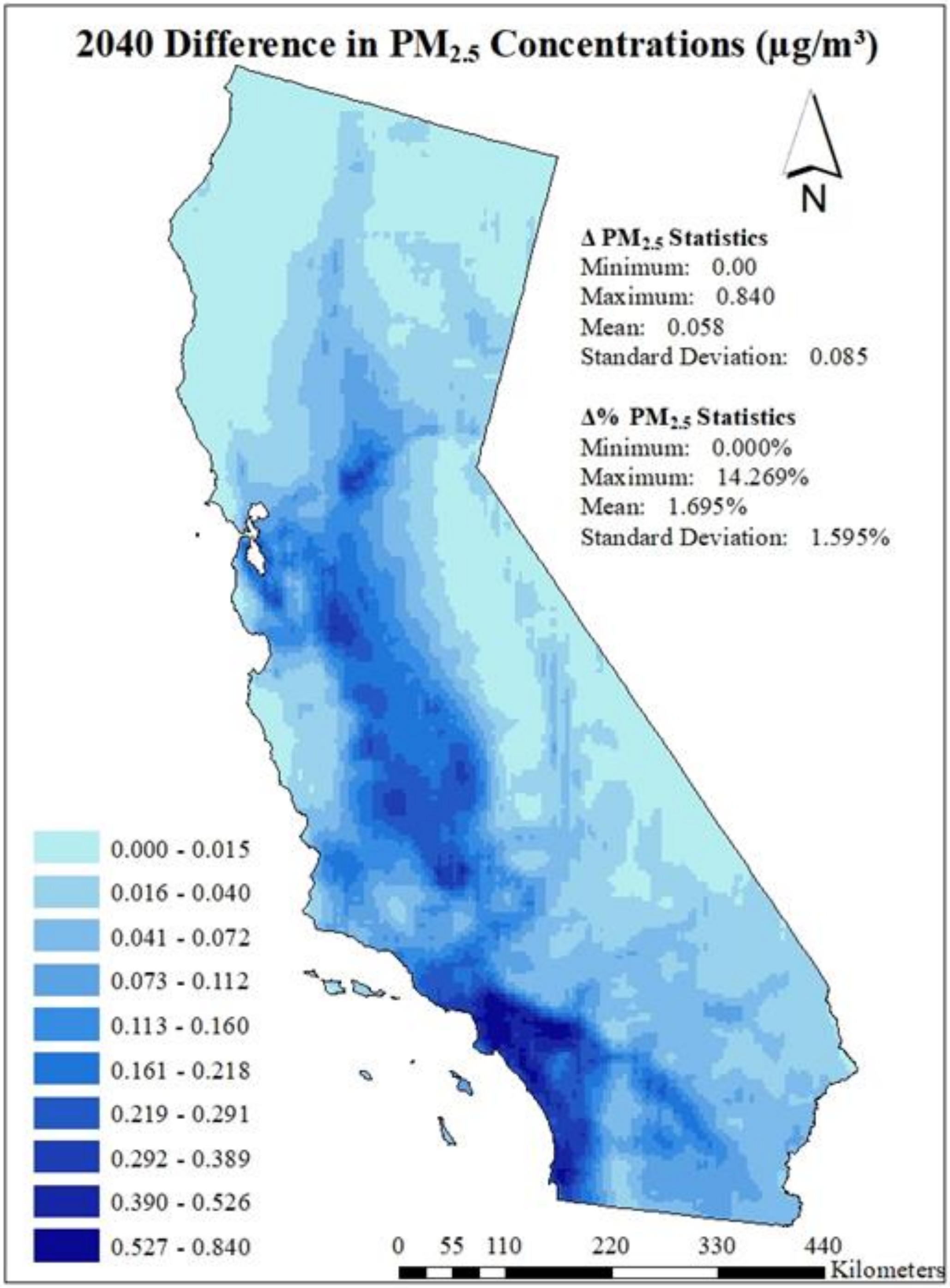


Figure 10.4. 2040 BAU and LC1 Difference in $PM_{2.5}$ Concentrations

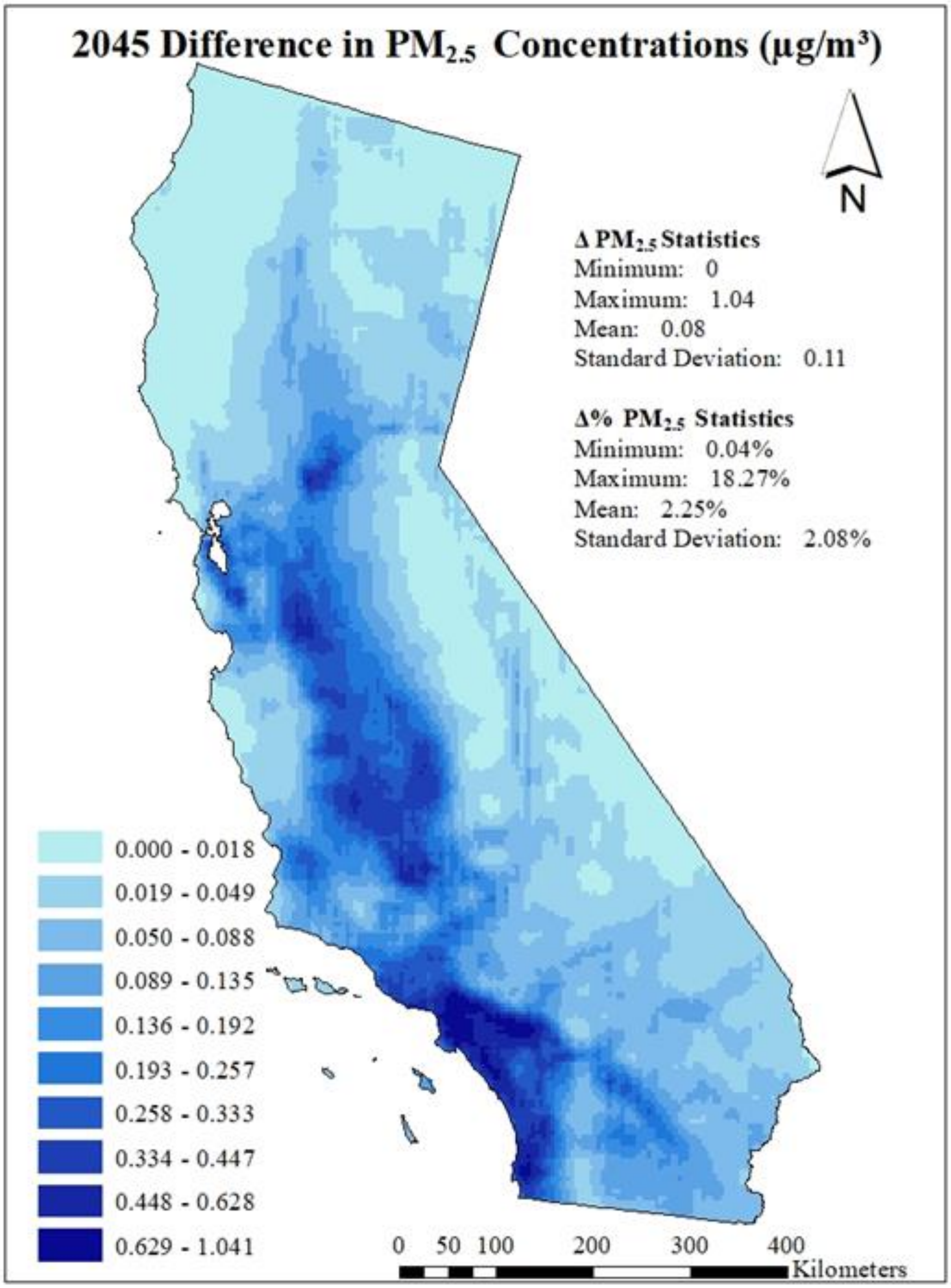


Figure 10.5. 2045 BAU and LC1 Difference in $PM_{2.5}$ Concentrations

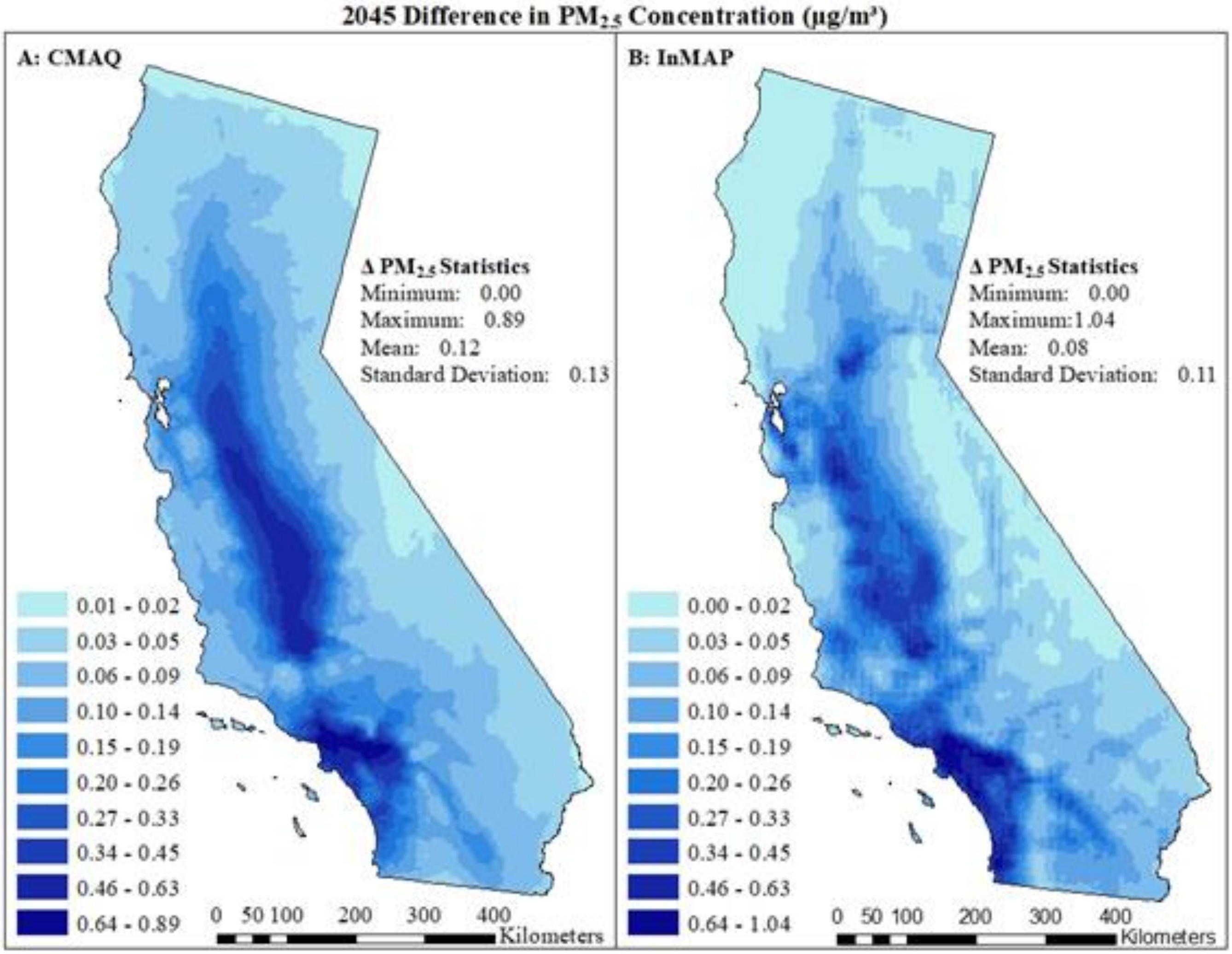


Figure 10.6. Comparison of changes in $PM_{2.5}$ concentrations in 2045 (BAU vs LC1). Panel A: CMAQ; Panel B: InMAP. Both CMAQ and InMAP maps use a 4 km x 4 km resolution.

10.3 Approach 2: CMAQ

10.3.1 Overview

An overview of the modeling methods utilized for the CMAQ assessment is provided in Figure 10.7. Using output from TTM, spatially and temporally resolved characterizations of criteria pollutants were developed for both the LC1 and BAU trajectories accounting for all major end-use sectors in California. Next, emission changes were translated into impacts on atmospheric pollution levels, including ground level ozone and $PM_{2.5}$, via the Community Multiscale Air Quality Modeling System (CMAQ), a 3-D photochemical air quality model that accounts for atmospheric chemistry and transport. Impacts on regional air quality were then assessed within the framework of disadvantaged communities to provide insight into benefits they may accrue with the decarbonization of the transportation sector.

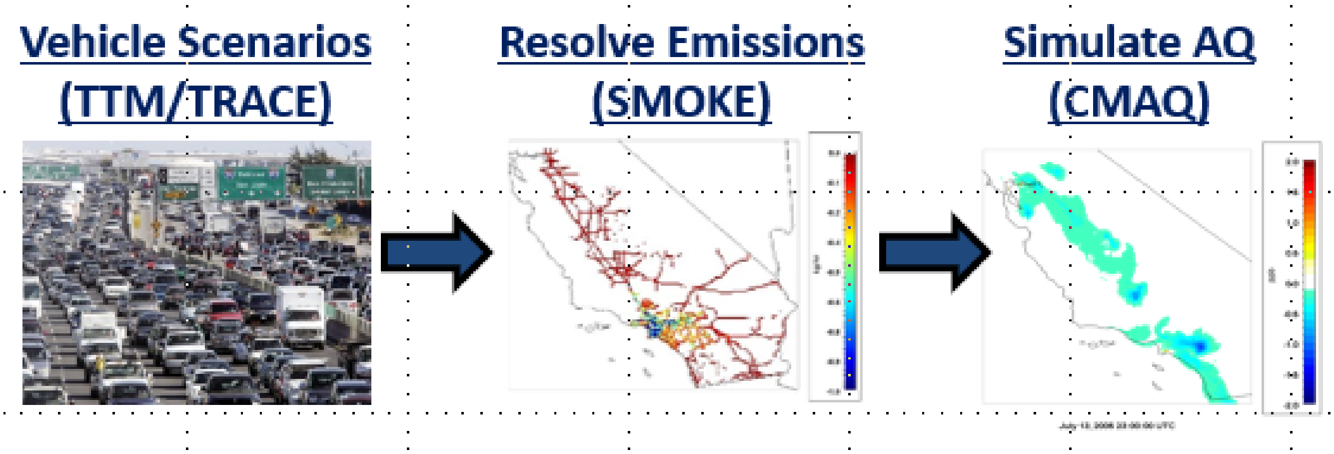


Figure 10.7. Overview of the CMAQ modeling methods utilized for the air quality assessment

10.3.2 Methods and Inputs

10.3.2.1 Key Assumptions

To obtain our results, we made a number of assumptions; we discuss the main ones in this paragraph. First, we assumed no changes in pollutant emissions associated with fuel production and distribution infrastructure. The reductions in petroleum fuel consumption in the LC1 trajectory will almost certainly lead to reductions in emissions from current petroleum fuel infrastructure including refineries, and fueling stations, for example. However, substantial uncertainties in how to allocate emission reductions as a function of fuel production complicate matters. For example, petrochemical refineries are large complex plants with many sources of emissions that produce many different products in addition to transportation fuels. How to quantify emission reductions from these facilities is still an open question. Further, a balanced assessment would also require accounting for sources of emissions from new fueling infrastructure for carbon neutral fuel production and distribution, e.g., emissions from the collection, harvesting, and transport of biomass feedstock, new biofuel facilities, and the trucking of produced fuels, to name a few sources. Such an assessment is outside the scope of work for this project. Therefore, only direct vehicle emissions were adjusted here to minimize uncertainty and provide an estimate of the air quality benefits associated with on-road vehicles. However, the potential fuel infrastructure impacts are important and should be considered in future work.

Several other assumptions which should be considered are listed below:

- Assumption 1: Emissions from brake and tire wear were held constant across all vehicle types including the replacement of conventional ICE vehicles with ZE vehicles. We made this assumption for simplicity although differences in vehicle weight or the presence of regenerative braking may make a difference, because of a lack of data.
- Assumption 2: Vehicles operating on RNG were assumed to have low-NO_x engines comparable to the current Cummins-Westport engines.
- Assumption 3: We assumed no change in emission rates for vehicles operating on renewable diesel or renewable gasoline/ethanol.

10.3.2.2 Emissions

To evaluate air quality impacts in 2045, we had to develop emission fields that account for differences in energy consumption and the technological composition of all end-use sectors. This requires two steps: 1) projecting emissions from current levels to the simulation period (2045) and 2) spatially and temporally allocating emissions throughout the modeling domain and period-consistent with the activity of emission sources.

For on-road vehicles, a California state-wide emissions inventory for 2012 developed by California Air Resources Board (CARB) was used as our baseline [324]. The 2012 emissions were then projected to 2045 using the output of TTM to produce emissions representing on-road vehicle fleets within the BAU and LC1 trajectories. The downscaling was accomplished by 1) using fuel consumption data from TTM and 2) projecting emission rates per unit fuel from EMFAC 2017 [57]. For all other sources, the 2012 emissions were projected to 2035 using statewide growth and control factors developed from CARB's CEPAM: 2016 SIP - Standard Emission Tool [325]. The CEPAM inventory accounts for current policy with implications for future emissions. At the time of this work (which started before the work from Approach 1), CEPAM projections were only available to 2035. To further project to 2045, output from the E3 California PATHWAYS Model was used with assumptions about energy consumption and technology deployment similar to those used in Aas et al. (2019) [326]. PATHWAYS is an energy infrastructure, energy and emissions counting model used to assess climate trajectories that meet California mandated goals. Here, the high building electrification trajectory from Aas et al. (2019) was used as it represents a low carbon outcome very similar to a carbon neutral outcome. It is important to note that these assumptions are held constant for both the LC1 and BAU trajectories. All the pollutant concentration differences presented here result only from differences in on-road vehicle emissions.

The second step was carried out using the Sparse Matrix Operator Kernel Emissions tool (SMOKE) version 4.0 [327]. SMOKE is an emissions processing system that develops appropriately formatted emission fields for air quality model input using a series of matrix calculations and allows for rapid and flexible processing of emissions data [328]. SMOKE carries out the core functions of emissions processing including spatial and temporal allocation, chemical speciation, generation of biogenic emission estimates and control of area-, mobile-, and point-source emissions.

The next section presents the change in criteria pollutant emissions for the LC1 trajectory relative to the BAU trajectory. Pollutant emission reductions from on-road vehicles in the LC1 trajectory relative to the BAU trajectory are shown in Figure 10.8. Reductions in all the pollutants considered are significant; they range from 39% for $PM_{2.5}$ to over 60% for SO_x. It should be noted that $PM_{2.5}$ represents only tailpipe emissions as those from brake and tire wear are held constant in vehicular trajectories (as indicate above). Reductions in total NO_x are approximately 50% from the BAU trajectory. These emission reductions also reflect the continued presence of legacy combustion vehicles in the LC1 trajectory, although they are operating on renewable fuels including renewable diesel.

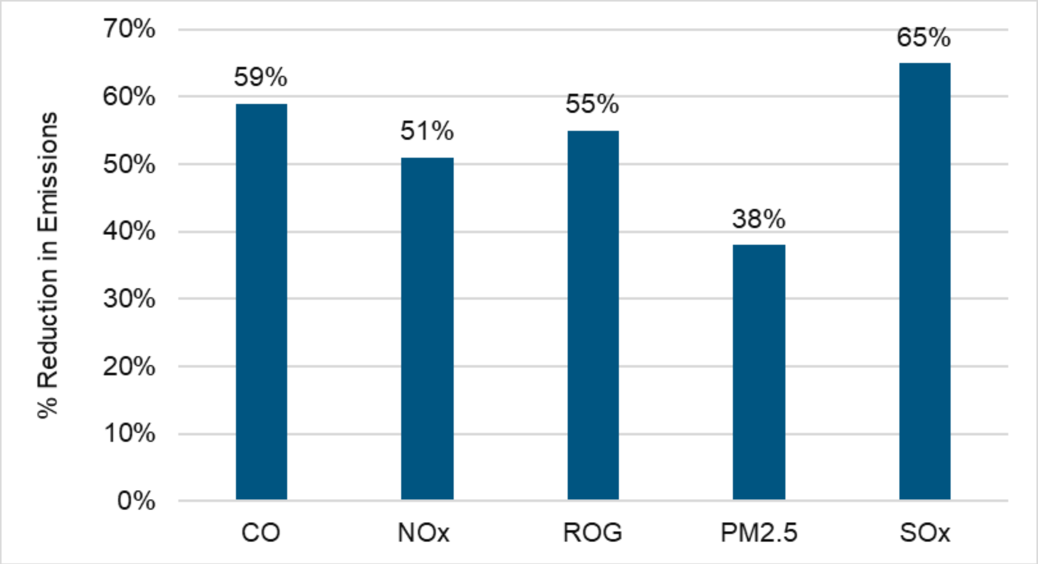


Figure 10.8. Emission reductions from on-road vehicles in the LC1 trajectory relative to the BAU trajectory.

Note: $PM_{2.5}$ emissions are tailpipe only. (ROG, reactive organic gas)

The emission reductions were then spatially and temporally disaggregated to the locations of vehicle activity as shown in Figure 10.9. Major urban areas, including the Southern California Air Basin (SoCAB) and the San Francisco Bay area would experience the largest reductions coinciding with high levels of vehicle activity. Major roadways are clearly visible throughout the state, including those extending throughout the Central Valley.

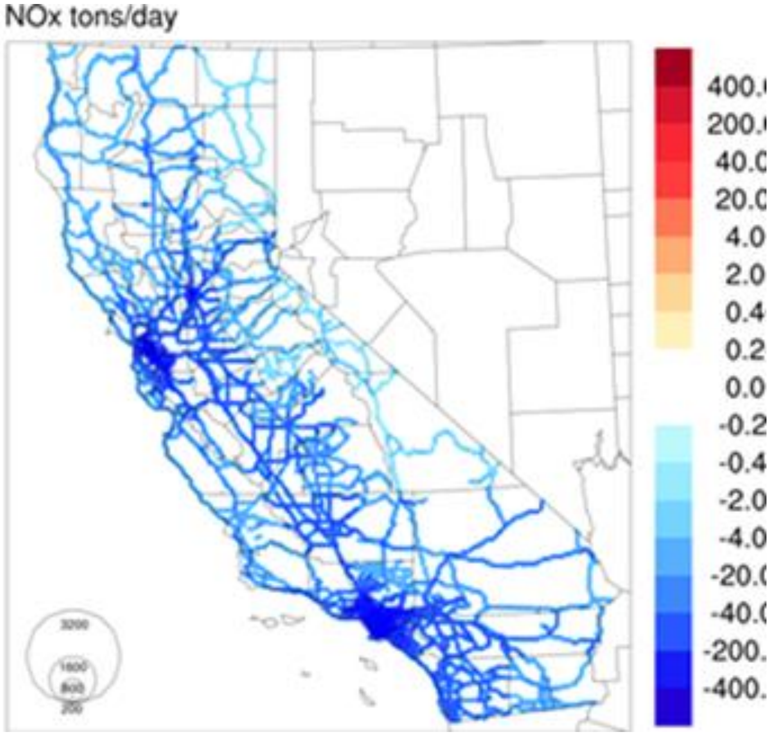


Figure 10.9. Difference in NO_x emissions in LC1 versus BAU.

10.3.2.3 Atmospheric Modeling Tools

Simulations of atmospheric chemistry and transport were accomplished via CMAQ v5.2 to provide a comprehensive estimation of pollutant concentrations, including ground-level ozone and $PM_{2.5}$ [329]. CMAQ is a comprehensive air quality modeling system developed by the US EPA. it is widely used for AQ assessments including regulatory compliance and atmospheric research associated with tropospheric ozone, PM, acid deposition, and visibility [330], [331]. CMAQ requires meteorological conditions, initial and boundary concentrations of atmospheric species, land use and land cover information, as well as emissions of both biogenic and anthropogenic sources. In this study, the SAPRC-07 chemical mechanism [332] was selected for gas-phase chemistry, and AERO6 module [333] was used to calculate aerosol dynamics. The simulation domain is the same as in Zhu et al. (2019) [334]; it covers the entire state of California with a horizontal resolution of 4 km x 4 km. The Advanced Research Weather Research and Forecasting Model (WRF-ARW, 3.7) was used to downscale meteorological conditions from the (Final) Operational Global Analysis data (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, National Center for Atmospheric Research, Computational and Information Systems Laboratory, 2000). Biogenic emissions were generated from the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGANv2.1) [335]. The boundary conditions came from the Model for Ozone and Related Chemical Tracers (Mozart v4.0) [336]. We compared simulation output with observational data and verified the statistical requirements for acceptable performance established by both the U.S. EPA and the research community [337]. Although simulations were conducted for the year 2045, both boundary and meteorology conditions were held constant as the base emission inventory year 2012, thus impacts of future changes due to transported pollution and climate were not considered. We ran annual simulations to capture the effect of seasonal variation in meteorology and emission signatures.

10.3.3 Output Data

Let us briefly discuss the impacts on regional air quality for the BAU and LC1 trajectories for NO_x, ozone and $PM_{2.5}$. We report differences in concentrations (LC1 trajectory - BAU trajectory) as a preliminary step to estimating the health benefits from decarbonizing the transportation sector in California.

Annual average changes in NO_x are presented in Figure 10.10. We observe peak improvements in SoCAB in excess of 2 ppb, which is substantial, and reflects the high levels of on-road vehicle activity concentrated within the region and contributing geographic and meteorological conditions. Though of lesser magnitude, additional improvements in NO_x are noted in other regions of California including the Central Valley, S.F. Bay, and San Diego County. The impacts are most pronounced in urban areas and localized to major roadways.

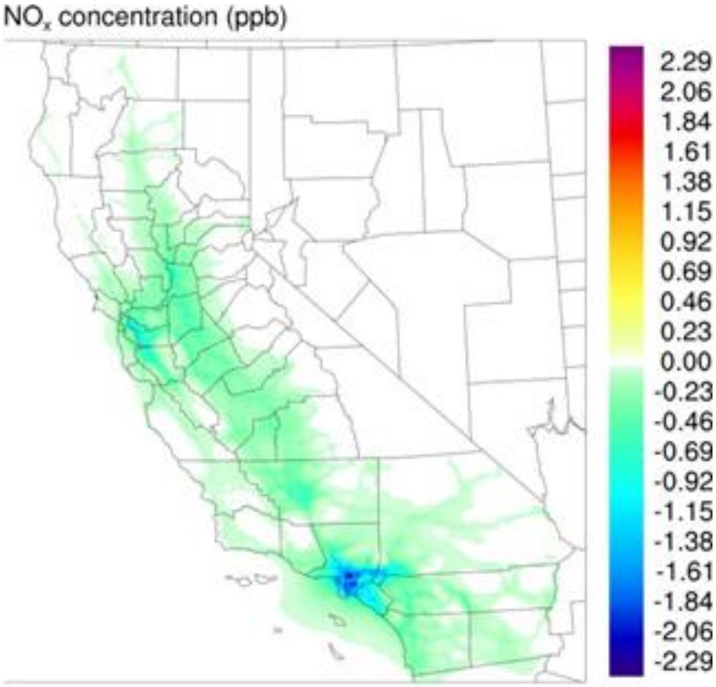


Figure 10.10. Difference predicted for the LC1 trajectory for annual average NO$_x$ concentrations

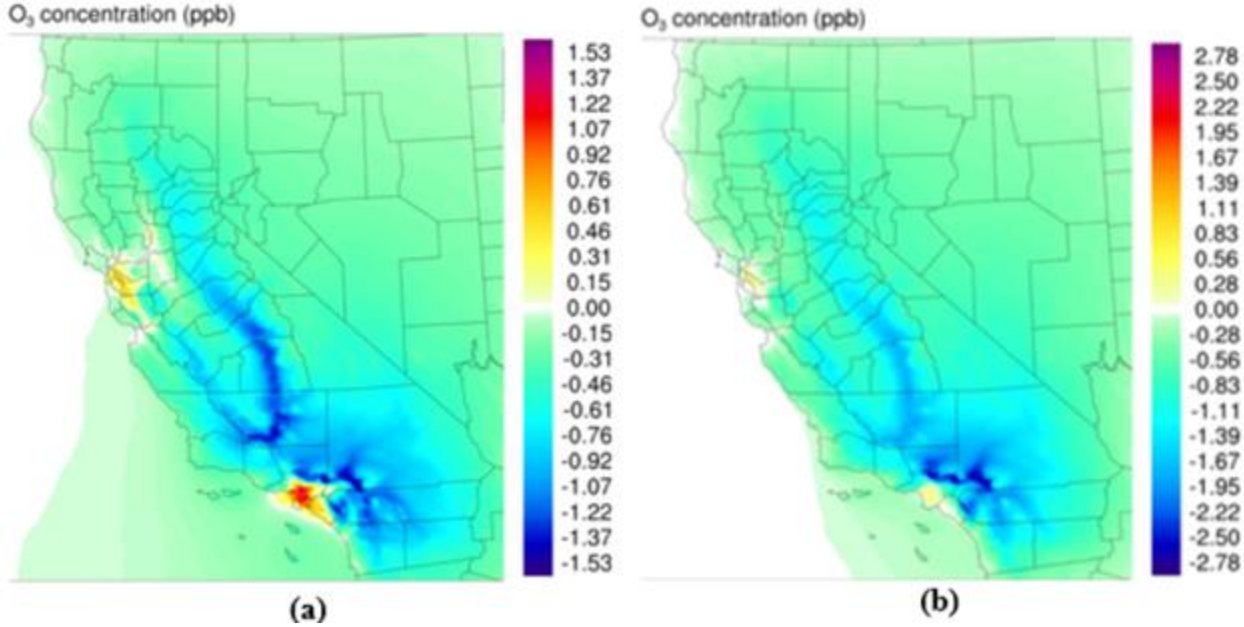


Figure 10.11. Difference predicted for the LC1 trajectory for (a) annual average ozone and (b) average MD8H ozone from April-October

The differences in both annual average and ozone season MD8h predicted for the LC1 trajectory are shown in Figure 10.11. Annual improvements in ozone reach -1.5 ppb while MD8H concentrations reach -2.8 ppb throughout the ozone season. Following the NO$_x$ trends, impacts are most pronounced in the same areas of the

SoCAB that experience the highest baseline ozone concentrations. Improvements are also noted in the Central Valley, reflecting the significant contribution of on-road vehicles to total pollutant burdens in those regions [338]. Conversely, areas of ozone increase are also visible in coastal regions of SoCAB. These come from decreased ozone titration because of significant NO_x reductions in the LC1 trajectory, a phenomenon that is well understood (e.g., see Fujita et al., 2003, or Pollack et al., 2012) [339], [340] and that has been demonstrated in a number of studies with similar reductions in NO_x [341]–[344]. While an increase is likely detrimental, it should be noted that the ozone concentrations in the BAU trajectory are generally low in these coastal areas; at the same time, we observed significant ozone reductions in highly impacted inland. Further, the NO_x reductions contribute to important $PM_{2.5}$ benefits in the same areas.

Improvements in annual $PM_{2.5}$ predicted for the LC1 trajectory reach -0.9 ug/m^3. As for ozone, reductions are most pronounced in SoCAB, although they are more uniform throughout the basin and thus impact large populations. We also observe substantial decreases in average annual $PM_{2.5}$ concentrations in the Central Valley, which frequently experiences episodes of non-compliance with NAAQS. These episodes occur seasonally. For example, stagnant conditions occur in the Central Valley in winter, which contribute to high $PM_{2.5}$ levels [337].

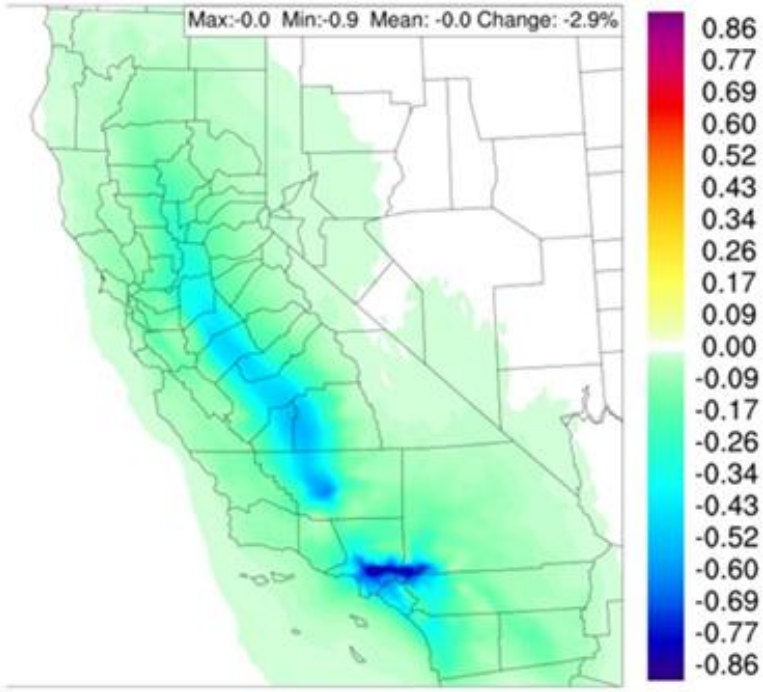


Figure 10.12. Difference predicted for the LC1 trajectory for annual average PM2.5

10.3.4 Disadvantaged Community Case Studies

To contextualize health improvements from decarbonization that could occur to disadvantaged communities (DAC), we estimated air quality improvements to two areas mostly inhabited by disadvantaged communities: the area around the ports of Los Angeles and Long Beach (the San Pedro Bay Ports, SPBP) in Southern California, and the Stockton area, in the Central Valley.

Figure 10.13 displays the difference in NO_x concentrations (LC1 - BAU) around the SPBP complex. These improvements reflect the switch under LC1 to zero emission for most vehicles operating in this area, including heavy-duty trucks associated with ports operations. Likewise, Figure 10.14 and Figure 10.15 show changes in annual $PM_{2.5}$ concentrations and in ozone concentrations, respectively. Due to the effects of decreased titration discussed above, communities in this area will likely experience slight increases in ozone levels resulting from significant NO_x reductions. However, the notable improvements in $PM_{2.5}$ are highly desirable as $PM_{2.5}$ generally represents the more important air pollutant in terms of human health in these communities.

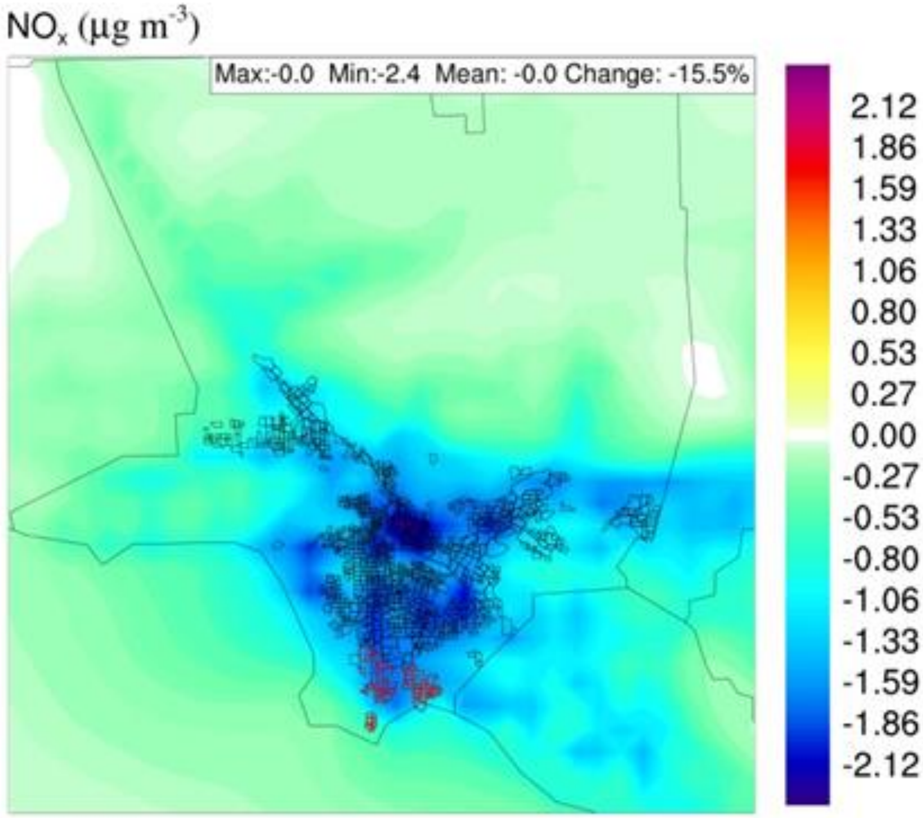


Figure 10.13. Annual average difference in NO_x concentrations (LC1 - BAU)

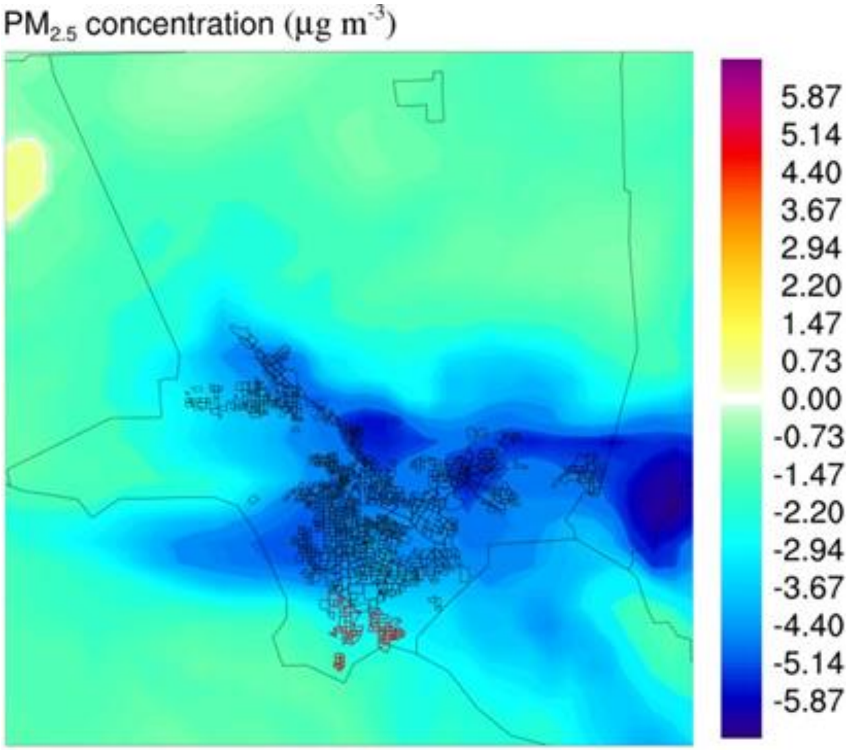


Figure 10.14. Annual average difference in $PM_{2.5}$ concentrations (LC1 vs. BAU)

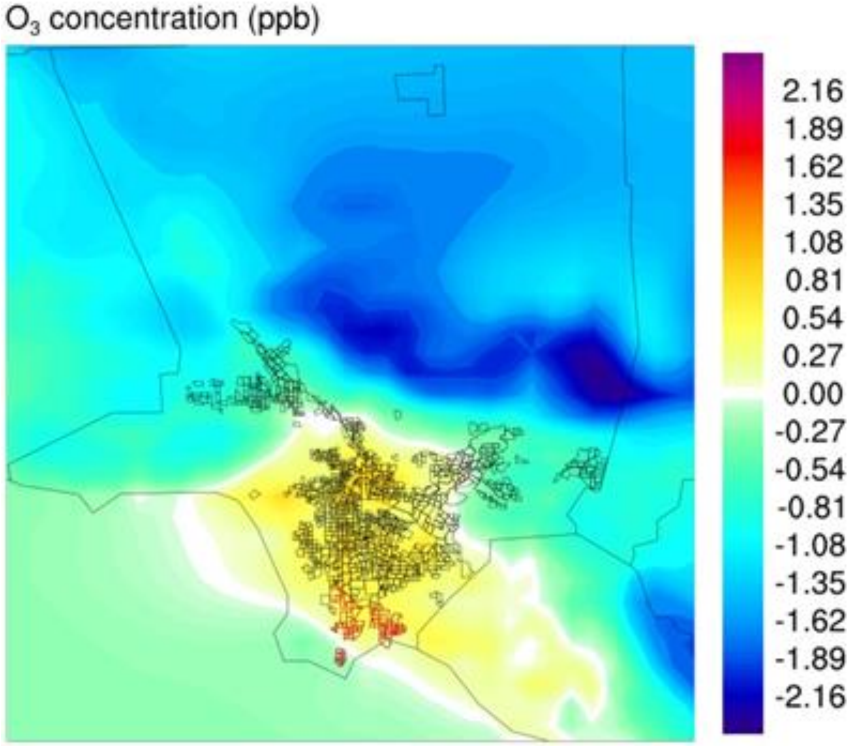


Figure 10.15. Annual average difference in MD8H ozone concentrations (LC1 vs. BAU)

Figure 10.16 displays reductions in NO_x concentrations (LC1 - BAU) in and around the Stockton area, where several disadvantaged communities reside. Figure 10.17 and Figure 10.18 show the corresponding reductions in annual $PM_{2.5}$ and ozone, respectively. Considering both the Stockton and Los Angeles area case studies, these results show that communities currently experiencing degraded air quality are likely to benefit substantially from the switch to zero emission vehicles under LC1.

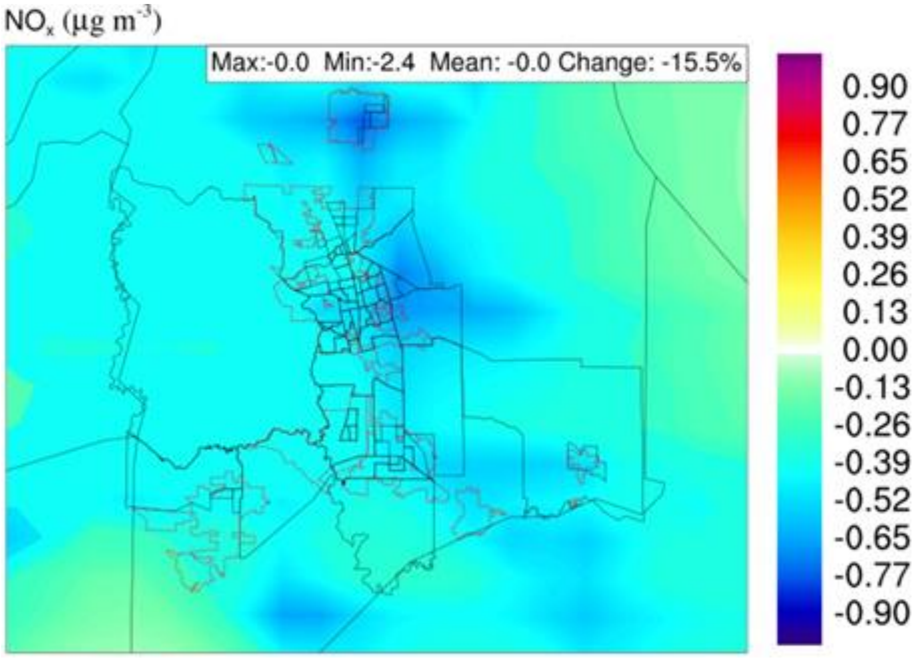


Figure 10.16. Annual average difference in NO_x concentrations (LC1 vs. BAU) with DAC outlined

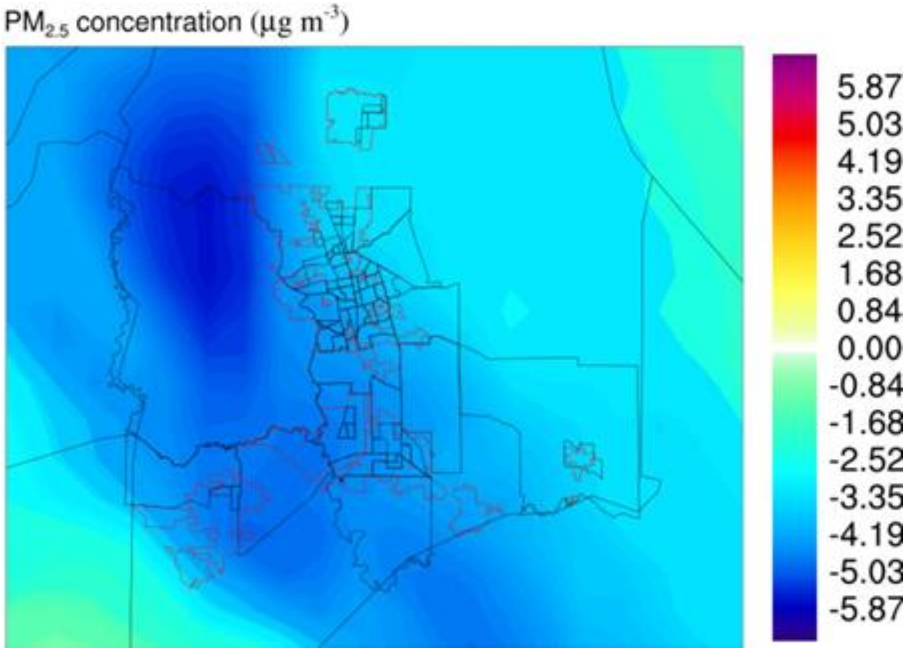


Figure 10.17. Annual average difference in NO$_x$ concentrations (LC1 vs. BAU) with DAC outlined

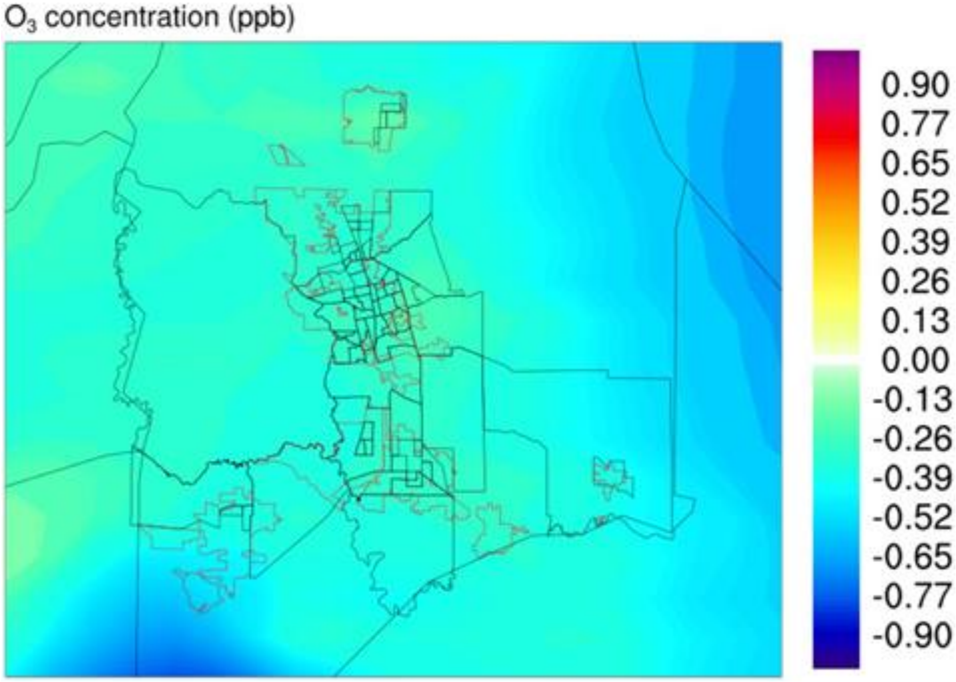


Figure 10.18. Annual average difference in MD8H ozone concentrations (LC1 vs. BAU) with DAC outlined

10.4 Assessment of Health Impacts using BenMAP

To quantify how changes in $PM_{2.5}$ concentrations between the BAU and LC1 trajectories impact selected health outcomes, we relied on EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) [345]. BenMAP combines data about the difference in air pollutants between a baseline and a scenario with spatially resolved population, concentration-response (C-R) functions, and baseline incidence rates for various health endpoints to quantify the resulting changes in selected health outcomes. It also monetizes these health outcomes.

Table 10.4. Concentration Response Functions Selected for the Health Analysis

	$PM_{2.5}$	Ozone
Mortality, All Causes	Krewski et al. (2009) [346]	Bell et al. (2005) [347]
Hospital Admissions, Cardiovascular	Moolgavkar (2000) [348] Zanobetti et al. (2009) [349]	--------
Hospital Admissions, All Respiratory	Zanobetti et al. (2009) [349]	Katsouyanni et al. (2009) [350]
Emergency Room Visits, Asthma	Slaughter et al. (2005) [351]	Mar et al. (2009) [352]
Hospital Admissions, Asthma	Babin et al. (2007) [353]	Moore et al. (2008) [354]
School Loss Days, All Cause	--------	Gilliland et al. (2001) [355]
Minor Restricted Activity Days	--------	Ostro et al. (1989) [356]

To select concentration-response (C-R) functions given the short timeline of this project, we first relied on U.S. and California studies for which the input data for BenMAP were readily available, after conducting a review of the epidemiological literature. In particular, we built on an analogous study conducted by the South Coast Air Quality Management District (SCAQMD) [357]. The selected C-R functions used in this study are shown in Table 10.4. We note that other recent studies for California have used similar CRF, e.g., [358]. The avoided all-cause mortality incidence associated with reductions in annual $PM_{2.5}$ exposure were estimated based on the results from Bell, et al. [346]. In two cases, lack of data availability required the selection of CRF from BenMAP directly including estimation of hospital admissions and emergency room visits for asthma symptoms associated with $PM_{2.5}$ exposure.

10.4.1 InMAP+BenMAP Results

For 2045 and every five years starting in 2025 (by design, there is no difference in 2020 between the BAU and the LC1 trajectories), we estimated the number of people affected by changes in annual average $PM_{2.5}$ concentrations calculated using InMAP. As explained above, natural and anthropogenic background emissions were obtained from the CARB inventory CEPAM while on-road emissions were estimated based on VMT from the statewide travel forecasting model (CSTDM), with emission rates from EMFAC.

Our population data for 2020 to 2035 come from Geolytics' census tract projections [359]. Population projections by age group at the census tract level were obtained by using 5 year geometric extrapolations, corrected to make sure that county totals match projections from the California Department of Finance [360].

We complemented BenMAP's default baseline incidence data with data extracted from the BenMAP regional datasets [345].

For 2045, $PM_{2.5}$ concentrations ranged from 5 to 15 µg/m^3 for our baseline and control scenarios (BAU vs. LC1), and the differences between these two ranged between 0 and 1.04 µg/m^3. $PM_{2.5}$ concentration differences are withing this range for intermediate years and are significant starting in 2030. $PM_{2.5}$ differences in 2025 ranged between 0 and 0.04 µg/m^3.

Our valuation estimates rely on a unit Value of Statistical Life (VSL) of $8.7 million (2015$) available in BenMAP. This VSL value is the mean of the distribution of 26 VSL estimates that appear in the economics literature and are identified by the Section 812 Reports to Congress as "applicable to policy analysis." Table 10.5 summarizes the expected health benefits associated with InMAP $PM_{2.5}$ concentration reductions for target year 2045 and intermediate years between the BAU and LC1 scenarios. It shows the number of cased for each selected health outcome and their corresponding monetized value in 2015$.

Based on InMAP results, the annual value of the reduction in premature mortality due to the cut in $PM_{2.5}$ emissions is approximately $31.4 billion by 2045. Figure 10.19 shows the trend of InMAP Health Benefits associated with $PM_{2.5}$ concentration reductions and compares 2045 results with CMAQ incidence and valuation results. Approximate 75% ($23.2 billion) of these health benefits are observed by year 2040, 39% ($12.2 billion) by year 2035, and 15% ($4.6 billion) by 2030. $PM_{2.5}$ reductions in 2025 were insignificant, thus health benefits were zero. Similarly, Figure 10.20 shows changes in the aggregated health endpoints considered and their valuation in the three major air basins (South Coast, San Francisco Bay, and San Diego County Air Basins). These results suggest that ~63% of the statewide health benefits were observed in the South Coast Air Basin, and ~11% in the San Francisco Bay and San Diego County Air Basin, respectively. The remaining 15% of statewide health benefits come from the San Joaquin Valley, the Sacramento Valley, and the South-Central Coast Air Basins.

Table 10.5. Estimated 2045 LC1 Health Benefits via InMAP+BenMAP

	Health Incidence Reduction	Health Benefits (million 2015$)
	Low Carbon Scenario 2025 Health Benefits	
Hospital Admissions, Cardiovascular	0	$0.00
Hospital Admissions, All Respiratory	0	$0.00
Emergency Room Visits, Asthma	0	$0.00
Mortality, All Causes	0	$0.00
	Low Carbon Scenario 2030 Health Benefits	
Hospital Admissions, Cardiovascular	67	$3.09
Hospital Admissions, All Respiratory	43	$0.02
Emergency Room Visits, Asthma	62	$2.08
Mortality, All Causes	532	$4,630.74
	Low Carbon Scenario 2035 Health Benefits	
Hospital Admissions, Cardiovascular	175	$8.10
Hospital Admissions, All Respiratory	107	$0.06
Emergency Room Visits, Asthma	164	$5.49
Mortality, All Causes	1,406	$12,236.81
	Low Carbon Scenario 2040 Health Benefits	
Hospital Admissions, Cardiovascular	329	$15.25
Hospital Admissions, All Respiratory	190	$0.10
Emergency Room Visits, Asthma	311	$10.39
Mortality, All Causes	2,665	$23,196.79
	Low Carbon Scenario 2045 Health Benefits	
Hospital Admissions, Cardiovascular	441	$20.44
Hospital Admissions, All Respiratory	418	$13.99
Emergency Room Visits, Asthma	243	$0.13
Mortality, All Causes	3,607	$31,396.20

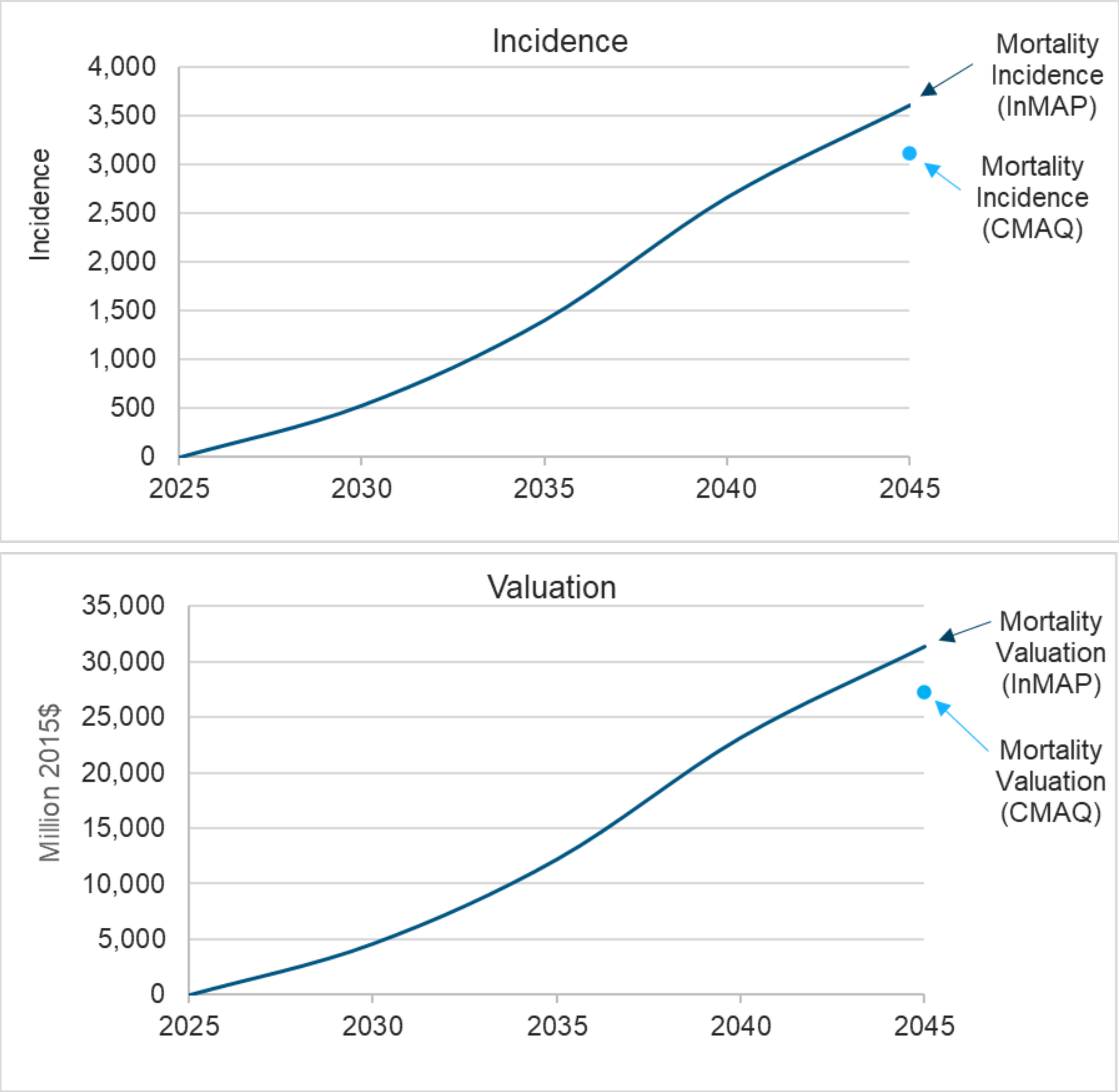


Figure 10.19. Statewide annual incidence and valuation health benefits

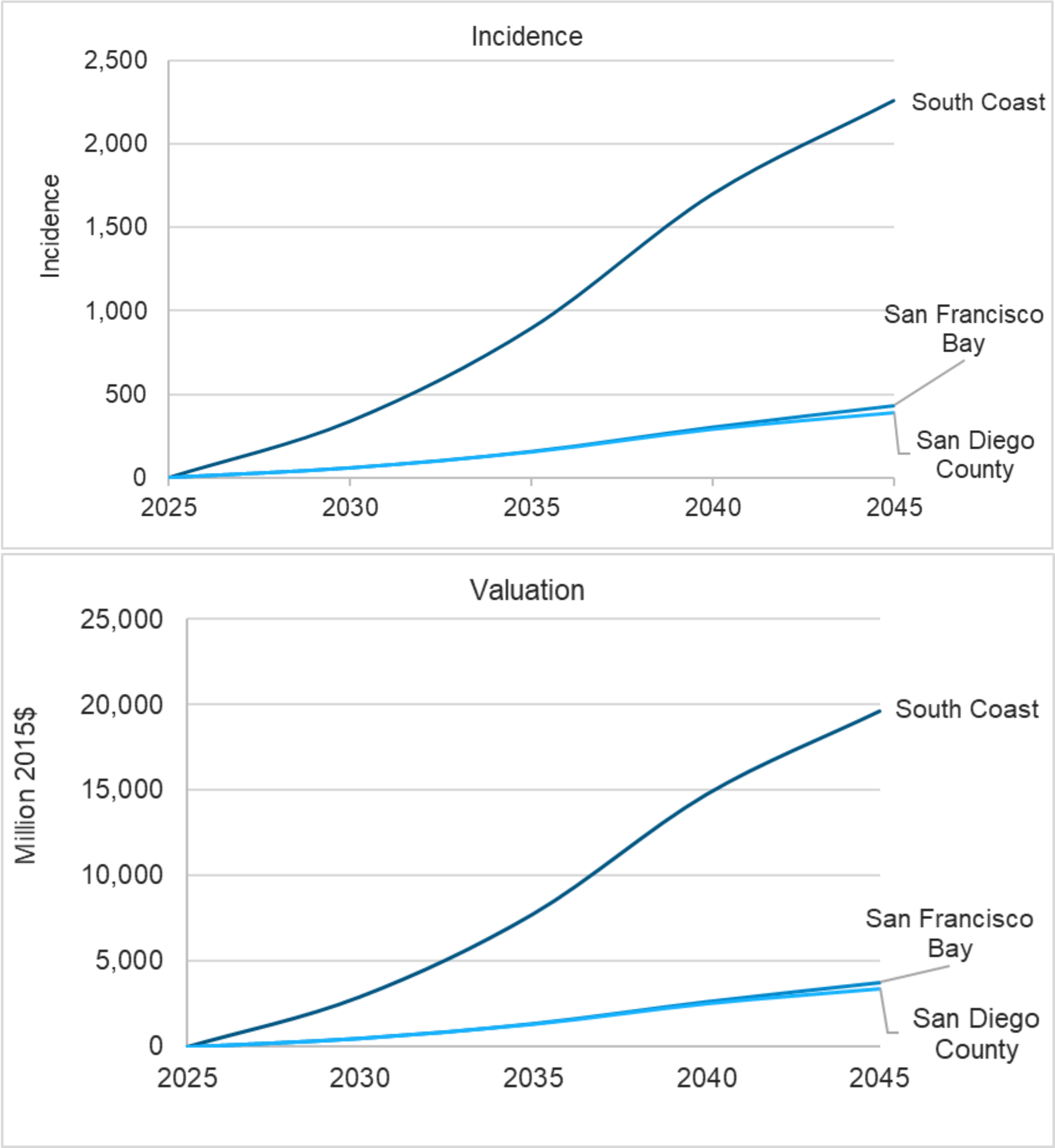


Figure 10.20. Annual incidence and valuation health benefits of major air basins

10.4.2 CMAQ+BenMAP Results

Table provides the estimated health benefits for the LC1 scenario relative to the baseline for reductions in ground-level ozone and $PM_{2.5}$ simulated in CMAQ. Avoided incidence of premature mortality are estimated for ground-level ozone and $PM_{2.5}$. Notable avoided incidence of morbidity are included for ozone including hospital admissions for asthma and other respiratory illness, school loss days, minor restricted activity days, etc.

The majority of avoided mortality incidence are associated with reduced exposure to $PM_{2.5}$, estimated to be 3,123 in 2045. Additionally, $PM_{2.5}$ improvements provide reductions in hospitalizations for various deleterious health effects including cardiovascular and respiratory illness. The results are moderately lower than the results for the same metrics estimated using InMAP which reflects the slightly more conservative reductions in atmospheric $PM_{2.5}$ concentrations predicted by CMAQ. For example, peak improvements in $PM_{2.5}$ within the study domain reach 0.9 ug/m^3 in CMAQ while exceeding 1 ug/m^3 using InMAP. The difference is explained by a range of factors that vary between the two modeling frameworks including the granularity and spatial distribution of emissions reductions, simulation of atmospheric chemistry, meteorological inputs, and others. Indeed, the similarity of the results is notable considering these differences and provides a measure of verification to these results. Improved ozone concentrations are responsible for an additional 111 avoided incidence of mortality. In total, the health savings that accrue are estimated to exceed $28 billion, the bulk of which is associated with avoided premature mortality from reduced $PM_{2.5}$ exposure ($27 billion). Avoided mortality from ozone exposure contributes approximately an additional $1 billion. Health savings from avoided ozone morbidity events provide only a minor portion of the total health benefits but are notable for significant reductions in hospital admissions for asthmatic episodes. Additionally, reducing ozone concentrations has important benefits for children including avoiding school loss and restricted activity days.

Table 10.6. Estimated 2045 LC1 Health Benefits via CMAQ+BenMAP

	$PM_{2.5}$		Ozone	
	Health Incidence Reduction	**Health Benefits (million 2015$)**	**Health Incidence Reduction**	**Health Benefits (million 2015$)**
Mortality, All Causes	3,123	$ 27,233.76	111	$970.82
Hospital Admissions, Cardiovascular	377	$17.47	--------	--------
Hospital Admissions, All Respiratory	335	$11.21	80	$1.80
Emergency Room Visits, Asthma	221	$0.12	1,860	$ 0.98
School Loss Days, All Cause	--------	--------	110,535	$24.24
Minor Restricted Activity Days	--------	--------	310,773	$ 5.55

Figure 10.21 shows the health savings allocated to the major air basins in California, with ~66% of the total health savings occurring in the South Coast. This is slightly higher than the proportion estimated via the InMAP method but is expected as the benefits from ozone are most pronounced in that region and InMAP does not account for those. Benefits in the San Joaquin and S.F. Bay represent ~9% each respectively, while those in San Diego and Sacramento accrue ~5% each.

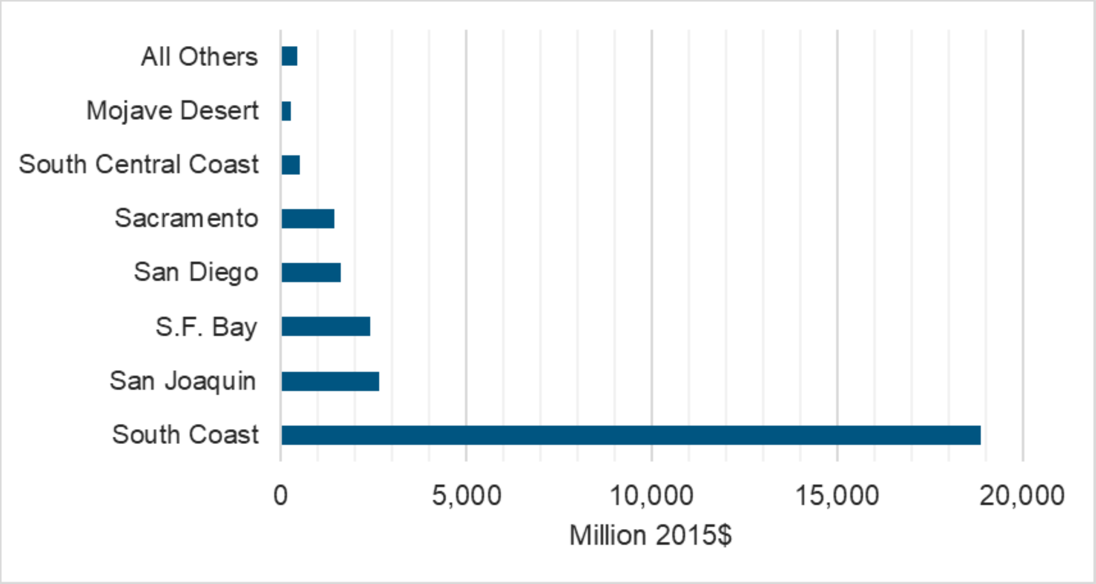


Figure 10.21. Valuation health benefits of major air basins in 2045 using CMAQ

Considering how improved air quality in the LC1 scenario provides benefits to DAC near the SPBP and Stockton, Table 10.7 reports the health savings for those communities specifically. For the SPBPC, 217 avoided incidences of mortality from improved $PM_{2.5}$ concentrations are reported which result in health savings of approximately $1.9 billion. Conversely, incidence of mortality from ozone experience a minor increase with a health penalty of $0.02 billion. The results show that the benefits within L.A. DAC are significantly net positive despite the slight increase in ozone from titration, e.g., health savings from $PM_{2.5}$ are generally much larger than those associated with ozone. For the Stockton area DAC, improved $PM_{2.5}$ results in 13 avoided incidences of mortality associated with $0.1 billion health savings. Ozone improvements have a minor impact in the Stockton DAC, but it is positive. Overall, the results demonstrate that the changes in vehicles in the LC1 scenario result in important air quality benefits within DAC, particularly from $PM_{2.5}$.

Table 10.7. Estimated 2045 LC1 Health Benefits within the selected DAC Communities

	Low Carbon Scenario 2045 Health Benefits in Selected DAC			
	Avoided Ozone Mortality Incidence	**Ozone Health Benefits (million 2015$)**	**Avoided PM2.5 Mortality Incidence**	**PM2.5 Health Benefits (million 2015$)**
Los Angeles	-2	-$20	217	$1,900
Stockton	0.4	$3	13	$114

11 Equity and Environmental Justice

11.1Current Policy

11.1.1 California's Commitment to Social Equity

Due in large part to community advocacy spanning generations, the State of California has consistently been at the forefront of environmental justice (EJ) policy in the United States. In 2001, California became one of the first states to codify EJ in statute with an official definition: "the fair treatment of all races, cultures, and incomes with respect to the development, adoption, implementation, and enforcement of environmental law [361]." In recent years, California legislators have issued a suite of policies aimed at directing investment towards and providing protections for disadvantaged communities (DACs).

These investments carry with them an explicit connection to EJ concerns. Notably, Senate Bill 535 (SB 535) (passed in 2012) channels proceeds from the state cap-and-trade program's Greenhouse Gas Reduction Fund (GGRF) to projects benefiting DACs. 2017's Assembly Bill 1550 (AB 1550) requires projects funded by the GGRF after that year to be located within (and directly benefit) DACs in order to count towards the 25% statutory investment minimums set by SB 535. As showcased in Figure 11.1, based on the 2020 California Climate Investment Legislative Report, 39% of the $2.6 billion GGRF funds allocated since 2017 have gone towards projects directly located in and benefiting DACs.

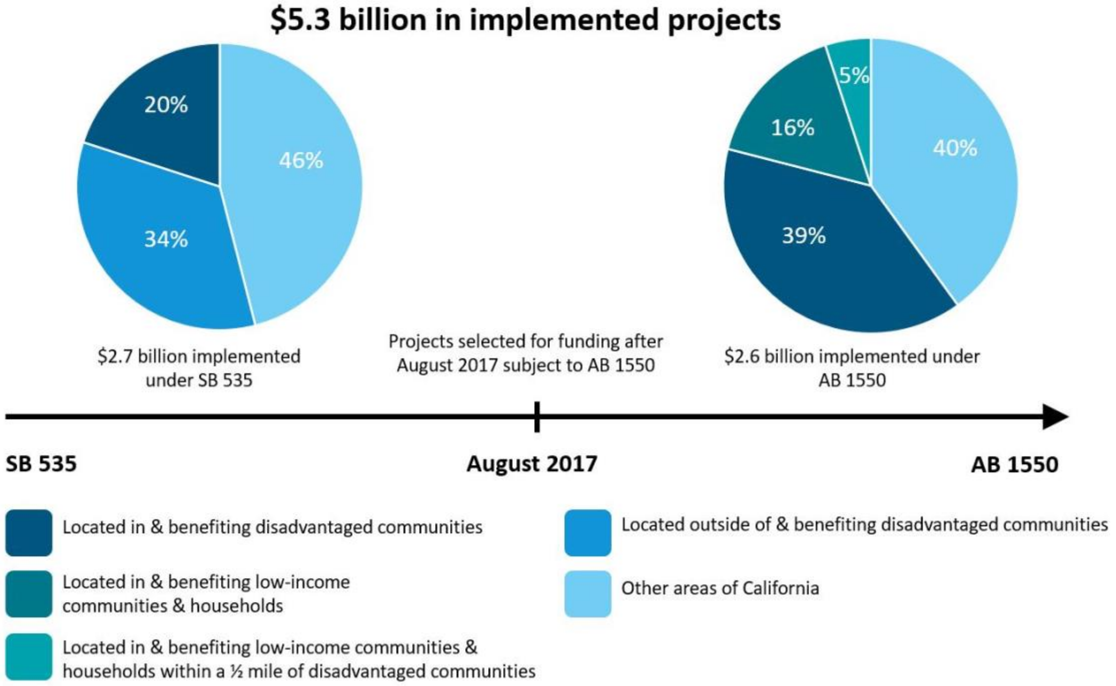


Figure 11.1. California Climate Investments for Disadvantaged and Low-Income Communities (Image source: http://www.caclimateinvestments.ca.gov/annual-report, pg.17)

In addition, California has made significant efforts in addressing the barriers limiting accessibility to clean transportation options for low-income, DAC, and tribal communities. Senate Bill 530 (SB 530), authored by State Senator Kevin de León, directed the drafting of a series of reports to identify and understand the challenges of such communities in securing clean transportation and mobility options. This resulted in pathways and implementation of programs targeting transportation equity by promoting active transportation, zero emission heavy duty vehicles, micro-mobility projects, and EV charging infrastructure funding in low-income, tribal, and disadvantaged communities.

11.1.2 CalEnviroScreen (CES)

The State of California has established numerous additional policies and programs meant to address social and environmental disparities statewide. Many of these policies and programs rely on CalEnviroScreen (CES), a map tool that identifies DACs based on a diverse suite of characteristics. Shown in Figure 11.2, CES is a publicly available tool that state agencies and local government agencies can use to identify these communities that are disproportionately affected by several metrics related to pollution. This tool is a production of collaboration between multiple state agencies, researchers, and a broad array of stakeholders, currently in its third iteration and housed at the California Office of Environmental Health Hazard Assessment (OEHHA). The tool is currently undergoing updates to release a 4.0 version of the CES tool in January 2021.

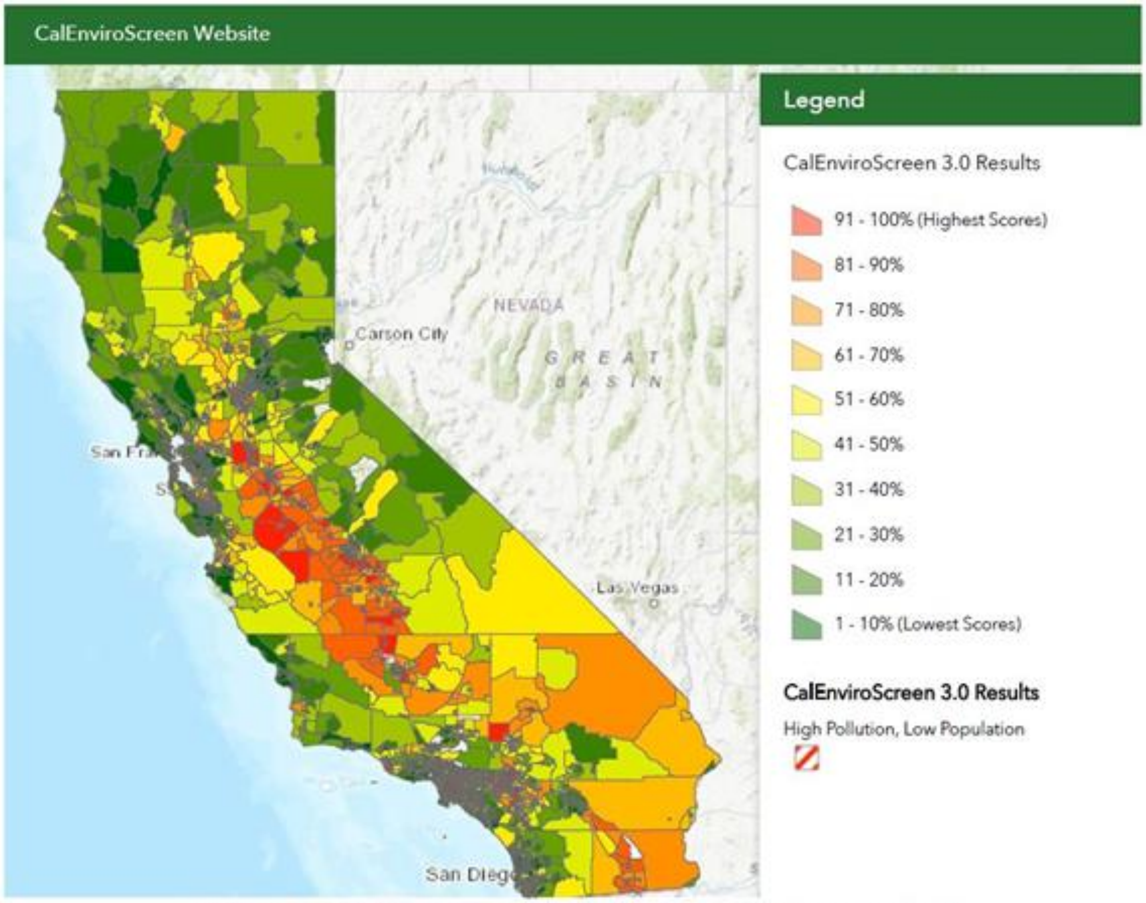
Soon after codifying EJ into statute, California created the state's first Advisory Committee on Environmental Justice to discuss strategies to integrate the principles of EJ into the state's regulatory agencies. It was clear from the outset of the discussions that the state's traditional approach to address environmental hazards on a "facility-by-facility, chemical-by chemical," strategy was omitting underlying factors that affected DACs.

To address these concerns CES developers introduced a Cumulative Impact (CI) method to comprehensively evaluate a community's vulnerability. CI is a method of analysis that takes into consideration multiple pollutants from various sources and accounts for socio-economic factors that can exacerbate health hazards when evaluating sensitive populations [362]. This method of analysis was key in developing a peer-reviewed, scientific tool that would holistically evaluate the environmental conditions in vulnerable communities.

After years of metrics evaluation and hosting various public comments sessions across the state, OEHHA in coordination with CalEPA published the first version of the CES in April 2013. For each census tract in the state CES creates a measure of cumulative burden—across multiple pollutants, socio-economic stressors, and health vulnerabilities—for that tract, relative to all the other census tracts in the state. The primary purpose of this tool is to quantify CI to identify communities in California that face the most challenging environmental and socio-economic conditions.

Currently, many of California's EJ policies rely on these CES metrics to determine the vulnerability of communities. Policies often use the 25% threshold to identify those census tracts where GGRF dollars should be targeted. The passage of AB 1550 increased the number of areas targeted for funding by including census tracts defined as low-income, in accordance with metrics defined by the state's Department of Housing and Community Development.

To address concerns over inaccuracies and relevance of stress indicators used in this tool, California continues to work with researchers, community groups, and stakeholders to modify the CES tool. Community stakeholders point to the limited consideration of race and ethnicity as a critical factor in marginalization that has produce many of the existing environmental inequities. Refining the metrics used in this tool ensures that factors that are contributing to adverse environmental conditions can identify vulnerable and priority communities with greater precision. Properly accounting vulnerable and priority communities across the state is key to allocate resources and mitigating efforts in communities that need it most.



Source: OEHHA. Available at: https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30.

Figure 11.2. CalEnviro Screen tool (Image source: https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30)

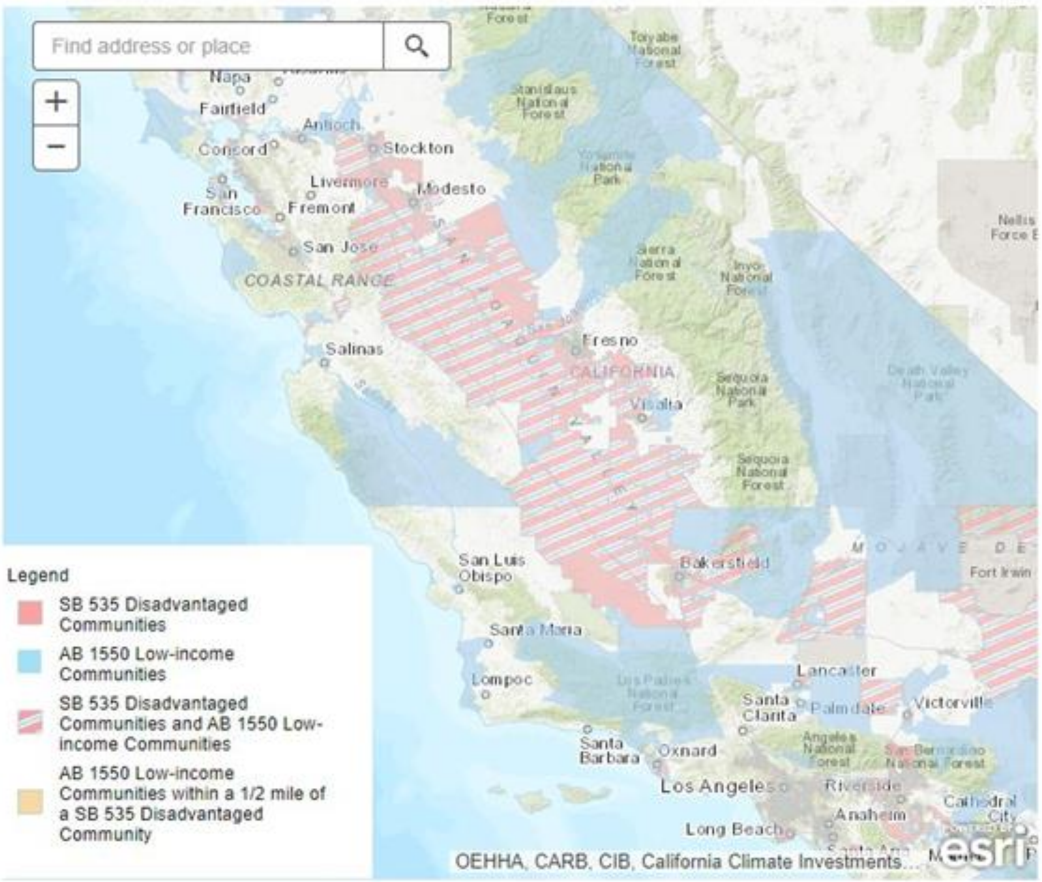


Figure 11.3. SB 535 Disadvantaged Communities and AB 1550 Low-Income Communities (Image from: https://oehha.ca.gov/calenviroscreen/sb535)

11.1.3 Equity Concerns and Feedback

Stakeholders participating in a statewide workshop for this study, (see section 14.5, Equity Appendix: Stakeholder Feedback) as well as an internal advisory group have provided EJ and equity-focused comments. These comments represent the concerns of community residents, community activist, and civic leaders that have built rapport and are well-attuned to the communities they advocate for. While not all comments provided are rooted in academic research, these concerns are evidence that academics and community stakeholders must continue to collaborate in tackling the pressing transportation and energy issues affecting EJ communities. Recognizing the history and lack of equity-related practices in carbon-neutrality research, community stakeholders—who represent community-based perspectives and have a long-standing commitment to advance EJ—expressed the following concerns. Stakeholders criticized the market strategies to decarbonize the State's transportation system; Specifically, the Cap-and-Trade program, characterizing it as an unsustainable system that relies on pollution to fund the transition to zero emission vehicle (ZEV) programs. Community stakeholders argue that the mechanics of the Cap-and-Trade can exacerbate environmental inequities if polluting operation can intensify. Furthermore, community stakeholders voiced their concerns regarding the effectiveness of these market strategies to dramatically discourage carbon emission, specifically in communities characterized with high percentage of low-income, people of color. Lastly, community stakeholders argue that programs like Cap-and-Trade do not provide an immediate environmental benefit but rather allocate the benefits in distant clean-mobility options, such as EV technology. In short, market strategies are placing an inequitable environmental burden in low-income, communities of color; in turn residents from these communities lack the financial resources to adopt and benefit from the new mobility technology supported by these programs

Other comments from Community Stakeholders included concerns over the lack of expert and administrative support for smaller, fiscally lean municipalities. Community Stakeholders indicated that providing such entities with the necessary resources would strengthen their effort to secure financial resources and ensure their fair share of the low-carbon transportation system. Stakeholders also recommended exploring "polluter pay" principles and financing mechanisms that ensure the fossil fuel industry takes responsibility for the harm it has inflicted on people and the planet. Furthermore, nonmonetary costs must be taken into consideration with the implementation of policies and practices. Stakeholders identified multiple concerns, with a primary focus on the risk of gentrification and displacement resulting from the projected investment in disadvantaged communities.

While many state agencies now have formal advisory committees focused on equity issues, it is imperative that policymakers and state agencies continue to work in collaboration with groups that have been committed to advancing EJ efforts and research in California for years. State agencies can improve coordination around engagement efforts and integrate stakeholder feedback from groups like the California Air Resources Board, Environmental Justice Advisory Committee, the California Energy Commission and California Public Utilities Commission Disadvantaged Community Advisory Group, and the California Public Utilities Commission Low-Income Oversight Board.

These groups represent diverse transportation and energy interests and allow for more inclusive policies to be developed to support social equity goals. Recognizing that there is already extensive work happening at the grassroots level, the State should seek to prioritize building upon these efforts by investing in the community work being done in the front lines. This work has primarily been led by individuals that have developed an extensive network and positive community rapport.

Stakeholder groups have voiced concern about the level of commitment to authentic community engagement that prioritizes ongoing communication and outreach with these groups by including community stakeholders early in the process, creating space for meaningful partnerships, and providing an iterative process for continued input. Being proactive in these efforts ensures that stakeholder input is accurately represented, minimizes the risk of extracting knowledge from community partners without reciprocating the assistance, and prevents past harms from being repeated.

Research in EJ communities, historically has engaged in an unbalanced power relation, with communities wielding less power. This dynamic has challenged efforts to develop working relationship with these communities and their leaders. Community stakeholders argue that practicing power-sharing would encourage more engaging collaboration and provide the skillset for communities to advance their priorities in the research-sphere.

Finally, it will be critical to clearly communicate the expected outcomes of this study and what policymakers intend to accomplish. There are opportunities to continue to work together and build momentum beyond this study, while also leveraging the impact of this work while the study has the attention of local and statewide leaders.

11.1.4 Equity and Environmental Justice

Low-income and disadvantaged communities are disproportionately burdened with the negative impacts from land development practices and transportation-generated pollution. Many of these inequities stem from discriminatory practices prevalent in the post-war period that redlined DACs. These communities were hindered by lack of investment and limited from securing the financial tools needed to accrue inter-generational wealth. In addition, redlined communities would eventually be targeted by real estate for the development of large-scale transportation infrastructure projects. Today, many of the previously redlined communities are burdened with significant adverse environmental and social conditions affecting their safety, health, and opportunities to improve quality of life.

California has begun to address the legacy of discriminatory practices by enacting several laws directing funding to EJ communities and requiring EJ to be a consideration in planning processes. Senate Bill 1000 (SB 1000) signed in 2016, requires local governments to identify EJ communities and address environmental inequities in various plans.

Policymakers in California have also recognized the importance of EJ at the local and regional levels. The Sustainable Communities and Climate Protection Act, approved with the passage of Senate Bill 375 (SB 375), established cyclical planning processes in 18 regions with the goal of reducing GHG emissions and achieving state policy goals. Among other things, the Act's Sustainable Communities Strategy (SCS) requirement addresses several co-considerations, including social equity.

Unfortunately, while each region has adopted an SCS plan, a 2018 CARB Progress Report on SCS milestones showed that California is not meeting its CO_2 emissions-reduction goals. Vehicle Miles Traveled (VMT) per capita is rising statewide. In the regions covered by California's four largest Metropolitan Planning Organizations (MPOs), commuting times have increased for both single-occupancy vehicles and public transit.

Community stakeholders participating in a statewide workshop (see 14.5, Equity Appendix: Stakeholder Feedback) have pressed and voiced their concerns over the need for Regional Plans like the SCS to integrate land-use, housing, and employment options. Taking a comprehensive approach would facilitate the broad adoption of practices that increase active modes of transportation, (e.g., walking, cycling), and the use of public transit. Stakeholders reiterated the need to comprehensively address land use issues in combination with providing affordable and accessible mobility options that prioritize positive health outcomes and equity.

Additionally, the Community Air Protection Program established in 2017 under Assembly Bill 617 (AB 617) requires localities to leverage local air agencies to reduce exposure to air pollution in the most impacted communities. The program includes incentives to deploy cleaner energy and more efficient technologies, requires retrofitting pollution controls on industrial sources, increases penalty fees, and increases transparency of emissions data.

11.1.5 Social Determinants of Health

According to the World Health Organization (WHO), contemporary understanding of health should be redefined to include the complex circumstances into which an individual is born. The conditions in the places where people live, learn, work, and play are important factors in determining health risks and health outcomes (WHO, 2020). These conditions are commonly referred to as social determinants of health (SDOH) and have become a major focus of attention when addressing contemporary public health dilemmas.

While medical care is crucial to the health and well-being of communities, SDOH expands the understanding of health to include other domains in an individual's life, including: economic stability, access to education, the social and community context, access to health care, and the built environment. The varying degree of quality in these key factors across communities has resulted in health disparities with some communities enjoying prosperous health, while others cope with adverse conditions that increase health risks.

Recently, these disparities and respective negative health outcomes have been exposed and magnified by the coronavirus pandemic (COVID-19). DACs not only suffer from an elevated number of COVID-19 cases but are at higher risk of death due to the underlying adverse conditions that affect health in many of these communities.

The SDOH framework takes a more holistic approach to health by considering socio-economic factors that can ultimately affect an individual's health and the opportunity to live healthy. This framework suggests that health outcomes are the result of factors other than medical care. The cumulative impact of these factors will aggregate to define an individual's health. Take for example how "poor health or lack of education can impact employment opportunities which in turn constrain income. Low-income reduces access to health care and nutritious food and increases hardship [363]." These hardships can ultimately result in high stress levels, triggering dangerous and unhealthy coping mechanisms that might result in substance or alcohol abuse and lead to a shorter lifespan.

A major critique of the existing medical system in the United States is that currently we have a system mainly focused on sick-care rather than health care. In other words, the current system is reactive to the needs and demands of patients who are already sick. By shifting the focus of health to address the SDOH, medical care would be more proactive in its mission to create healthy and clean environments by reducing the propensity of individuals becoming sick and make strides in reducing longstanding health disparities [364].

Health research acknowledges that access to quality health care only has a 10%-20% impact on an individual's overall health [365]. Individual behavior, genetics, social circumstance, and build environments are all factors that have a more profound impact on an individual's health. In fact, research has found that directing financial resources towards social services that increase quality of life are much more effective in increasing public health. The benefits of investing in quality social services far outweigh the benefits from exclusively spending in health care resources [365].

Lastly, the SDOH identifies that community health should not simply be the purview of medical practitioners and researchers, but rather be at the forefront of multiple disciplines. Business, education, planning, housing, and transportation should all consider their role and impact on a community's health. By working to mitigate negative health impacts burdening communities, steps can be made towards an environment that promotes prosperity, well-being, and health in our most vulnerable communities.

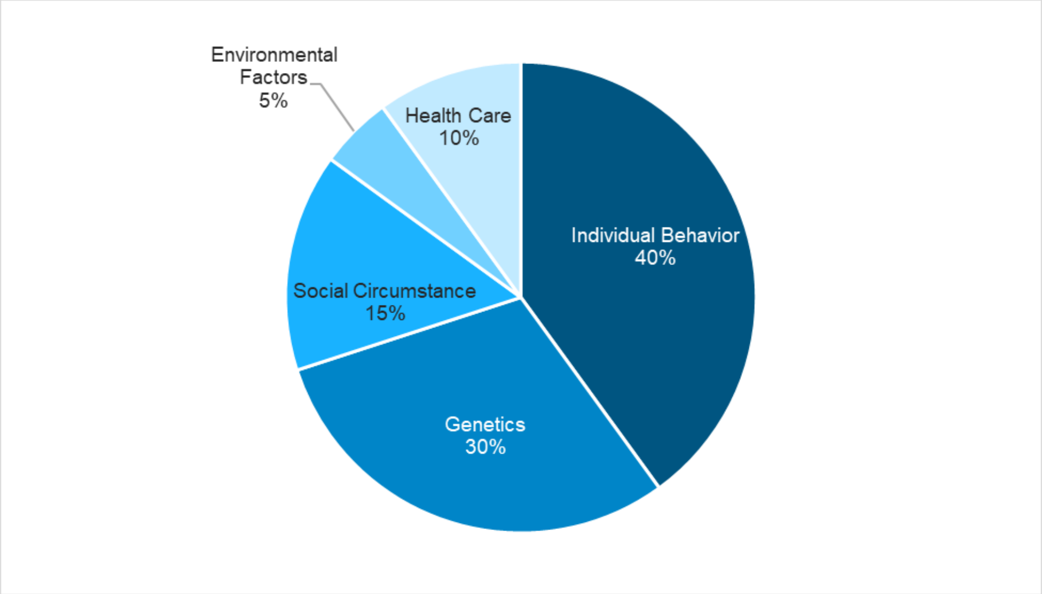


Figure 11.4. Breakdown of the Social Determinants of Health. Image from: http://www.modernmedicaid.org/medicaid-managed-care-plans-address-social-determinants-of-health/ (Data for image from: https://www.nejm.org/doi/full/10.1056/nejmsa073350)

11.1.6 Transportation and Health

The SDOH framework identifies the built environment as a key factor that affects health risks and outcomes. As part of the built environment, the current and future low-carbon transportation system has a direct impact on community health. The cost and time of travel between daily duties can significantly impact quality of life. Access to transportation not only provides connectivity to health care and other key health resources, but the transportation system itself can serve as an agent to promote or damage community health [366].

Among the most pressing health issues related to transportation is air quality. Motor vehicle emissions produce particulate matter such as nitrogen oxides and carbon monoxide that contribute to air pollution [367]. High exposure to these on-road pollutants has lasting health impacts in communities living in close proximity to high-traffic arterials and freeways. Historically, these areas are characterized with high percentages of low-income, racial, and ethnic minority populations [147]. Consequently, these communities are most vulnerable to the adverse environmental conditions that result in elevated levels of childhood asthma, bronchitis, and other cardio-vascular diseases [368]. Increased levels of on-road pollutants also contribute to environmental degradation in the local hydrology, depletion of soil nutrients, deteriorating tree canopy, damaging agriculture, and contributing to the increased in the frequency of severe weather events.

Community stakeholders participating in a statewide workshop (see 14.5, Equity Appendix: Stakeholder Feedback) raised concerns about how the adoption of new technologies should be intentional while keeping in mind the equity and health impacts of different technological advances. Investment and deployment of ZEVs, both for heavy-duty and passenger vehicles, can have the greatest impact in EJ communities. Stakeholders participating in the statewide workshop emphasized the importance of prioritizing investment in zero-emission sources, noting that investments in technologies such as biofuels or proposed solutions like carbon capture storage and sequestration allow low carbon operations to be perpetuated without expanding zero emission (ZE) fuel infrastructure in EJ communities. Lack of investment in ZE technology can delay addressing deteriorating air quality that continue to harm EJ communities.

While policies and incentives that mitigate emissions are key in the transition to carbon neutrality, community stakeholders participating in a statewide workshop agree that this effort should also involve an aggressive reduction in air pollutants through resources to promote carbon stores. Amenities such as Urban Tree Canopy (UTC) can simultaneously reduce carbon emissions and pull carbon out of the atmosphere. In a study of UTC availability in cities across the U.S. (Schwarz et al., 2015), evidence suggests that there is a strong correlation between income and levels of UTC, highlighting the cities of Sacramento and Los Angeles as places where race and ethnicity were a strong indicator for low levels of UTC. Limited resources in low-income communities can affect the consistency and reliable maintenance operations for UTC. Moreover, limited political weight in minority communities hinders organized demand for such amenities that can contribute to better local air quality and favorable environmental conditions.

Safety from vehicle collisions is also an important component to community health. According to a CDC report (2012) [369], injuries from vehicle collisions are the leading cause of death in the United States for ages 1 to 44, while the WHO reported more than 1 million road traffic deaths in 2010 worldwide. Communities that lack proper signage and speed-reducing infrastructure in their neighborhoods result in severe health implications. The higher propensity of vehicle collisions in a community affects travel mode choice; dangerous conditions for pedestrians and cyclists discourages active transportation, and cumulatively lowers levels of physical activity. The built environment is key to ensuring community safety, thus the hazard of vehicle-collisions will continue to threaten community health if the transportation system is solely focused on phasing out fossil fuel vehicles with clean mobility resources.

Community stakeholders providing the equity lens for this study identified street safety as a primary concern, specifically in communities with heavy-duty vehicle (HDV) traffic. Stakeholders suggest that the health and economic effects of pedestrian-vehicle collisions pose a serious immediate threat, while the impacts of exposure to on-road pollutants are largely viewed as a potential long-term risk. Providing safe pedestrian conditions can increase community health, but more importantly, it can make the built environment an asset that contributes to positive health outcomes. shift the built environment as an agent that provides favorable living conditions.

11.1.7 Beyond Carbon Neutrality

There remain strong concerns about the assumption that carbon neutrality will equitably benefit California communities, especially considering the historic lack of investment and the disproportionate impacts that transportation-related pollution has had on disadvantaged communities and Black, Indigenous, People of Color (BIPOC). Community stakeholders have vocally expressed concerns (see 14.5, Equity Appendix: Stakeholder Feedback) that the communities most impacted by past discriminatory policies are likely to be further removed from this work or not in positions of decision-making power to influence the policies and practices that will result from this study. Therefore, it remains critical that these perspectives are not overlooked and that it is not assumed that communities approve of the roadmap forward if they are not given a voice in the decision-making process.

Furthermore, it is also imperative that state agencies and policymakers are held accountable for the commitments they make to disadvantaged communities. For example, dedicating personnel that specifically focus on advancing commitment to EJ and successfully executes deliverables to community partners. Community stakeholders have previously raised concerns that many research or policy efforts promise positive outcomes but fail to deliver tangible benefits for their communities. Groups have pointed to the example that some General Plans have included robust housing elements to address the current housing crisis in California, but they have yet to be operationalized.

This demonstrates the need for viable policies and practices that can realistically be implemented to realize the benefits of this research. It will be critical to clearly communicate the expected outcomes of this study and what policymakers intend to accomplish. There are opportunities to work together and build momentum beyond this study, while also leveraging the impact of this work while the study has the attention of local and statewide leaders.

11.2Site Studies

11.2.1 Los Angeles Area

The Los Angeles port area is one the most important points for commerce and trade in the United States. This point of entry provides goods and supplies for the western half of the country. Due to the consistent flow of traffic, idling of heavy-duty trucks, and the shipping vehicles, the surrounding areas are subject to harsh environmental conditions. Communities in this area face poor air quality, high levels of pollutants, and concerns over pedestrian safety in the streets. Therefore, this study has selected this region for a refined overview of this area and the potential benefits this area can expect in the transition to a low-carbon transportation system.

Figure 11.5 below identifies the selected census tracts for this area. The geographical limits for these selected communities were: Western Avenues as a western boundary, Interstate 405 as the northern boundary, Lakewood Boulevard on the eastern boundary, and the California coastline as the southernmost boundary. The selected census tracts were within the County of Los Angeles spanning various municipalities for a total of 75 census tracts. Based on the CES scores the most impacted communities are within proximity to the port operations and adjacent to the 710 freeway, a major freight corridor. Communities in the western boundary are in more affluent residential areas that have relatively better environmental conditions.

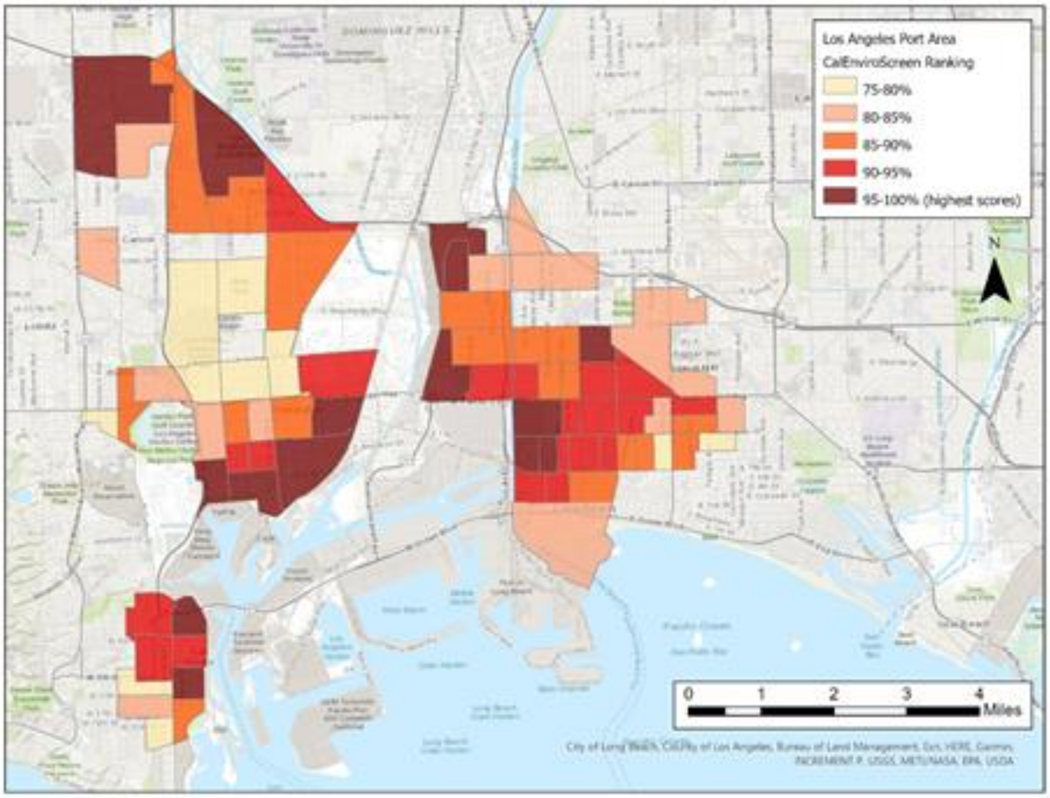
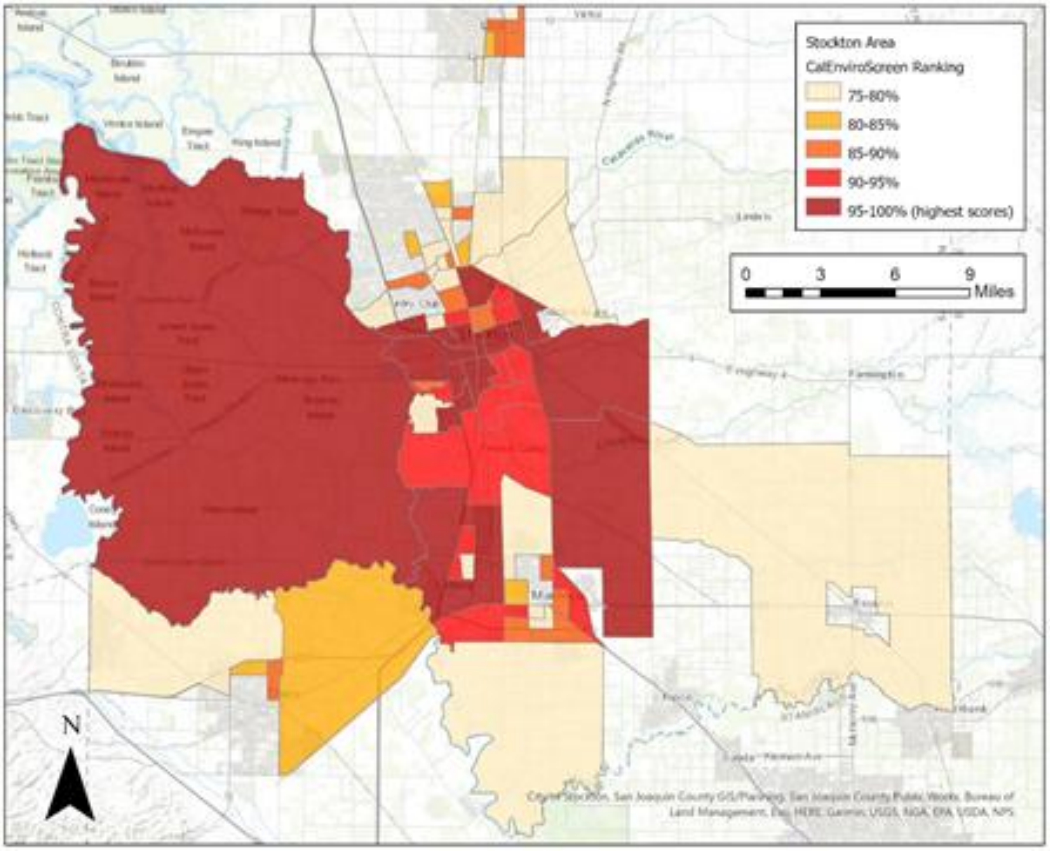


Figure 11.5. Disadvantaged communities in the Los Angeles Port Area

11.2.2 Stockton Area

Rural communities in California's San Joaquin Valley are burdened with some of the state's worst air quality. Large scale agriculture businesses, consistent freight operations along the state's major freeways, and sprawling urban centers have created harsh environmental conditions. The high demand for manual labor in this region represents opportunities for poor, immigrant populations from Mexico and other Central American countries, who are most vulnerable to these adverse conditions in this region. To better understand the conditions and potential benefits from a transition to a low-carbon system in the San Joaquin Valley, this study has selected communities in the Stockton Area.

Figure 11.6 below identifies the selected Stockton and neighboring communities. This area is characterized by an industrial core in the central business district of the City of Stockton. Connectivity to delta waterways that lead to the San Pablo Bay anchor the western census tracts. Large scale agricultural operations are common in the eastern and southernmost census tracts. Most importantly, this area is one of the few places in the state that has direct access to both of the states' parallel arterials, Interstate 5 and State Highway 99. While these highways are key to California's profitable agriculture sector, the figure below depicts communities in the vicinity burdened with adverse environmental conditions.



City of Stockton, San Joaquin County GIS/Planning, San Joaquin County Public Works, Bureau of Land Management, Esri, HERE, Garmin, USGS, NGA, EPA, USDA, NPS

Figure 11.6. Disadvantaged communities in the Stockton Area

12 Workforce Impacts and Relevant Policy Considerations

12.1 Introduction

Achieving carbon neutrality in California's transportation sector is projected to create over 7.3 million full-time equivalent (FTE) job-years of employment over the next 25 years. These new jobs will be a part of new multi-billion dollar economic sectors, such as refueling infrastructure and electricity as transportation fuel. Much of the novel job growth spurred by this transition will likely be within industries and occupations that currently offer high-quality jobs in terms of unionization rates, wages, and benefits, and which are accessible without requiring a bachelor's degree.

This influx of new jobs in zero-emission vehicle (ZEV)–related sectors must be considered alongside the accompanying, substantial decline in jobs related to fossil-fuel-burning internal combustion engine vehicles (ICEVs). It is important to recognize that these workforce contractions arise as a result of several ZEV trends that are themselves beneficial to Californian consumers, businesses, and government entities, and which are discussed further below.

Analysts project that even in the absence of the ZEV transition, the ICEV-related workforce will contract as a result of declines in maintenance costs and fuel consumption arising from the projected gains in fuel economy and shrinking of the on-road fleet. Such improvements in fuel economy and fleet shrinkage shape the job market independently from policy strategies—such as those considered in this study—that aim to shape consumer behavior to maximize the public good.

Furthermore, even in industries with large numbers of jobs that continue to exist while transitioning to support ZEVs instead of ICEVs (e.g., automobile maintenance), workers will need to expand their skill sets to adapt to new technology types. This will necessitate a workforce transition regardless of the relative magnitudes of gross job changes resulting from the expansion of new sectors such as charging infrastructure. Therefore, it would be inaccurate to view the current point in time as some sort of inherently stable status quo against which future conditions should be measured.

12.1.1 Section Overview

The primary value of this analysis is to highlight trends in ZEV-related job creation and ICEV-related job loss, independent from each other, and to use these trends to identify the specific industries and occupations that we are confident will be highly impacted by transportation decarbonization. These highly impacted areas are those that will see a significant degree of expansion or contraction in the coming years. Workers in these industries will be those in greatest demand as ZEV-related industries expand or, alternatively, those in greatest need of access to local and regional job placement and retraining programs.

To inform the development of such programs, we provide an overview of highly impacted worker characteristics that will be useful in identifying potential policy models for state-supported local transitional action, with special attention paid to just transition elements. Where data are available, we provide demographic profiles, wage and benefit figures, and a discussion of geographic distribution for the highly impacted industries identified. We supplement this with a discussion of policy models that can potentially be implemented on a wider scale to ensure equitable access to newly created jobs, promote practices that will boost the quality of said jobs, and ameliorate the negative impacts on workers in certain industries. Achieving carbon neutrality in transportation represents an opportunity for government to improve the economic well-being of hundreds of thousands of California workers. In doing so the state can go against historical precedent by adopting the principles of a just transition, extending these benefits to marginalized communities that have borne an outsized share of fossil fuel-related impacts in the past.

12.1.2 Study Limitations.

The task of forecasting future conditions is rife with uncertainty, especially when nascent industries and unprecedented expansion of technologies are involved. The inherent limitations to economic input-output modeling—discussed below—contribute further to this uncertainty. These uncertainties and limitations make it challenging to compare projected jobs to existing ones in certain occupations or to state with confidence how net jobs figures will change in any one area. We explicitly address the most pertinent of these challenges below and discuss their potential impact on the forecasted results.

As a consequence of these challenges, the overall net impact of California's transition to ZEVs on the state's workforce is uncertain. Regardless of the forecasted raw numbers presented below, real-world conditions not reflected by the model have the potential to create significant increases in realized jobs from expanding ZEV-related sectors and reduce the negative job impacts from ICEV-related sector contraction.

12.1.3 Focus on Job-years, Occupations and Industries

Our model output results are discussed in two forms: full-time equivalent (FTE) job-years, and annualized FTEs. A single FTE job-year represents sufficient economic activity to support the equivalent of one employee working full-time for one year. Such employment could take multiple forms, including two 50% part-time employees working for one year or one 50% part-time employee working for two years. The model does not allow us to predict which employment features—such as unionization rates or usage of independent contractors—will manifest in expanding industries in the future, which matter greatly for the future wages, benefits, and job security for workers filling these jobs. Our discussion of these job aspects focuses on current patterns in industries predicted to expand. Annualized FTEs are estimates for FTEs generated by expenditures made in a given year, which may or may not be realized in that specific year.

We refer to three distinct employment categories in discussing the characteristics of areas highly impacted by the transition: industries, occupations, and workers. *Industries* refers to employers or groups of employers that encompass and depend on many different types of employees to deliver goods and services; for instance, Oil and Gas Extraction employs a variety of engineers, operators, and managers (among other employees) with a range of skills. *Occupations* are types of jobs defined by a particular skill-set or set of duties, such as petroleum engineers within Oil and Gas Extraction. A given occupation may be used across many different industries (such as executives) or may be relatively specific to one or a few industries (such as petroleum engineers). *Workers* refers generally to employees of firms predicted to be impacted by the transition to ZEVs, and it is at times used interchangeably with *occupations*.

Our discussion of workforce impacts is sequenced as follows:

1. Explanation of the overarching method by which we translate forecasted consumer expenditures to changes in the job market.
2. Discussion of model limitations and key contextual factors important to consider in viewing the model results.
3. Presentation of the overall model results.
4. Presentation of sector-specific model results, accompanied by profiles of the workforce in the most significantly declining or expanding industries, key policy questions that arise from these data, and relevant policy discussion to answer those questions.

For a full detailing of the expenditure analysis and modeling process and a more robust presentation of results, please see the forthcoming technical report *Workforce Impacts of Achieving Carbon-Neutral Transportation in California* (working title) published by the UCLA Luskin Center for Innovation (hereafter referred to as the Technical Report).

12.2Our Approach for Forecasting Workforce Trends

The fundamental strategy used to assess the workforce impacts of California's transition to ZEVs is to project future expenditures within the state on transportation-related goods and services and to use these estimates to forecast job creation driven by said expenditures. Labor forecasts are modeled using IMPLAN Pro version 3.1, an economic input-output model, with the 2018 California State Total data package. Economic input-output models map the interdependent relationships between various industries and supply chains, including the ways in which outputs from one industry (e.g., refined metals) are utilized as inputs in another industry (e.g., EV manufacturing). Analysts are thus able to gauge the ripple effects that spread throughout an economy following purchases of goods and services occurring in particular industries.

Expenditure estimates are non-specific with regards to source; expenditures made by consumers, businesses, and governments are all amalgamated in a single total figure. With regards to jobs created to meet the demand such expenditures generate, the exact source of the money spent is inconsequential in economic input-output modeling. The expenditure projections upon which the model relies cover the following key categories:

1. *New Vehicle Sales*, distinguished by the three predominant drivetrain technologies (ICEV, battery electric vehicle [BEV], and fuel cell electric vehicle [FCEV]) and four vehicle categories (LDVs, MDVs, HDVs, and Buses). Used vehicle sales are not considered as they have significantly less impact on the overall labor market than do new vehicle sales. Sales of new hybrid and plug-in hybrid vehicles are not considered.
2. *Fuel Consumption for Transportation* across the three predominant fuel types: fossil fuels, electricity, and hydrogen. Fossil fuels incorporates consumption of both gasoline and diesel.
3. *Maintenance and Repairs* for vehicles, calculated across the four aforementioned vehicle categories and by ICEVs versus ZEVs (where ZEVs encompasses BEVs and FCEVs, discussed separately).

4. *Construction and Installation of New Transportation Fueling Infrastructure*, including the construction of new EV charging stations and hydrogen refueling stations and the installation of new electric vehicle supply equipment (EVSE) for residential, public, and workplace charging.

Data underlying these estimates largely come from the low-carbon scenario (LC1) and affiliated study teams. These data include projected vehicle sales figures, vehicle purchase prices, vehicle miles traveled (VMT), fuel consumption, and electric vehicle (EV) charging demand. Supplemental data from external sources are used where required, and include estimated maintenance costs by drivetrain technology and vehicle class, electricity generation technology trends, hydrogen refueling station capacity trends, and cost breakdowns for fueling infrastructure construction. For an in-depth walkthrough of the methods underlying the expenditure forecasting analysis and modeling, see the Technical Report.

12.3Model Background and Limitations

The outputs from this model estimate the workforce impacts of the forecasted transportation-related expenditures across three categories. ***Direct jobs*** are those in industries supplying goods and services on which money is being spent, such as BEV manufacturing workers and hydrogen refueling station staff. ***Indirect jobs*** are created in industries within the supply chain of those where direct jobs are created, such as workers refining the raw metals and materials from which BEVs are built. Finally, ***induced jobs*** represent those supported through broader economic activity stimulated by the creation of direct and indirect jobs; examples include grocery store workers and health care providers.

Job totals specific to a given year are presented in full-time equivalent jobs (FTEs) to provide a consistent unit of comparison. When discussing job creation over multi-year time periods, figures are presented in FTE job-years, which combine the annual amount of work with the time period over which it is conducted. For instance, one FTE job that persists over 5 years would be presented as 5 FTE job-years for that time period.

Input-output models carry a number of limitations that are important to understand. The most salient of these are briefly overviewed here; for an in-depth discussion, see the Technical Report.

- *Static Relationships*: The model captures economic relationships with industries as they were in 2018 and does not reflect any fluctuations or dynamism that may alter these relationships in the interim or in future years. Notably, economic disruptions resulting from the COVID-19 pandemic are not reflected in the model results.
- *Linear Relationships*: The model assumes that the scaling of workforce impacts in a given sector is linear with respect to expenditures, not reflecting potential variation in labor demand based on industry size or economies of scale. For instance, an expenditure of $100 million in a given industry will generate exactly 100 times the workforce impacts as a $1 million expenditure in that industry.
- *Timing of Impacts*: The model does not specify when particular job gains will be realized. A flood of money into a given industry may result in some degree of immediate or near-future job creation, while other jobs in supporting supply chains or those induced from general increases in economic activity may occur at a later time. In presenting the results below, job figures for a given year are presented as those occurring as a result of expenditures made in that year.

In addition to these inherent limitations of the model, there are several key contextual factors relevant for this study that impact the model results. These are reviewed in Appendix 14.6.

All model results were produced using aggregate expenditures over 5–6-year periods, specific to the various sectors considered. These raw totals are available in the Technical Report. The resulting job creation figures were then disaggregated to provide year-by-year job estimates, per methods detailed below.

12.4Forecasted Workforce Impacts

We next present amalgamated results for predicted job creation in expanding ZEV-related sectors and losses in declining ICEV-related sectors.

Overall, the model projects that between 2020 and 2045, California’s transition to ZEVs will create over 7.3 million full-time equivalent (FTE) job-years of employment through expansion of ZEV-related industries (Figure 12.1). As we explore further below, new BEV sales are consistently the largest ZEV-related sector in terms of generated employment, responsible for a majority of ZEV-related job realization until the early 2030s and a plurality thereafter. These figures encompass sales-related jobs (e.g., car dealership salespeople) as well as second-order jobs related to the production of these new vehicles (e.g., in-state BEV manufacturing). In the later years, a significant amount of job growth is generated from labor-intensive maintenance industries for the ever-growing BEV and FCEV fleets. Despite the increase in demand for electricity as a transportation fuel, this sector is predicted to only generate modest job growth; job gains related to new FCEV sales and hydrogen fuel consumption are similarly small. Construction and installation of new EV charging capacity accounts for a sizeable number of jobs in the later years of the study, but begins to shrink in size in the final years as demand for new infrastructure decreases. Jobs related to construction of new hydrogen refueling infrastructure are minimal by comparison.

Total job growth peaks at an estimated 514,000 FTEs realized in 2045. In the final years considered, there is a trend of the ZEV economy expanding at a rate of approximately 10,000 FTEs per year, likely indicating that employment in ZEV-related sectors will continue to expand after 2045.

Contractions in industries related to ICEVs and fossil fuels are predicted to simultaneously lead to a gross reduction of slightly over 730,000 FTEs when comparing 2020 and 2045 (Figure 12.2). Figure 12.2A shows the magnitude of employment generated by California’s ICEV-related sectors as fossil fuel-burning vehicles are phased out, while Figure 12.2B provides a complimentary representation of the magnitude of declines in employment for these sectors. The greatest number of these reductions occur in jobs related to ICEV maintenance, which decline from over 400,000 FTEs in 2020 to less than 100,000 in 2045. A small fraction of jobs related to fossil fuel consumption also persist through to 2045, as millions of vehicles requiring gasoline and diesel fuels are predicted to still be on the road at that time. In contrast, jobs related to new ICEV sales are expected to essentially cease to exist after 2040, down from over 250,000 FTEs in 2020. This is the logical outcome of a cessation of new fossil fuel-burning vehicles in the state after 2040, as reflected in the scenario.

As we did not model the business-as-usual scenario to determine workforce impacts, we do not have a valid baseline over time against which to compare employment in ICEV-related sectors. Therefore, we cannot state with confidence the total FTE job-years lost due to the contraction of these sectors.

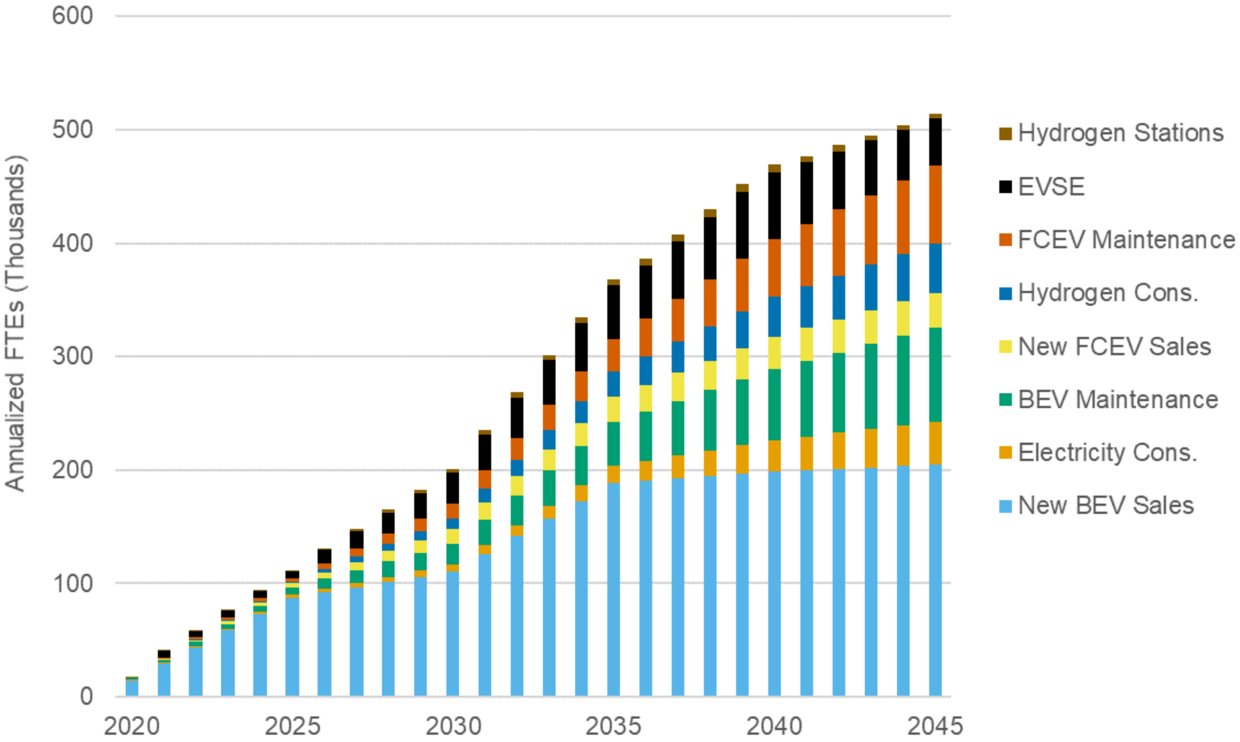


Figure 12.1. Projected estimates for annual total FTEs resulting from expansion of ZEV-related industries in California in thousands of FTEs by sector, 2020-2045.

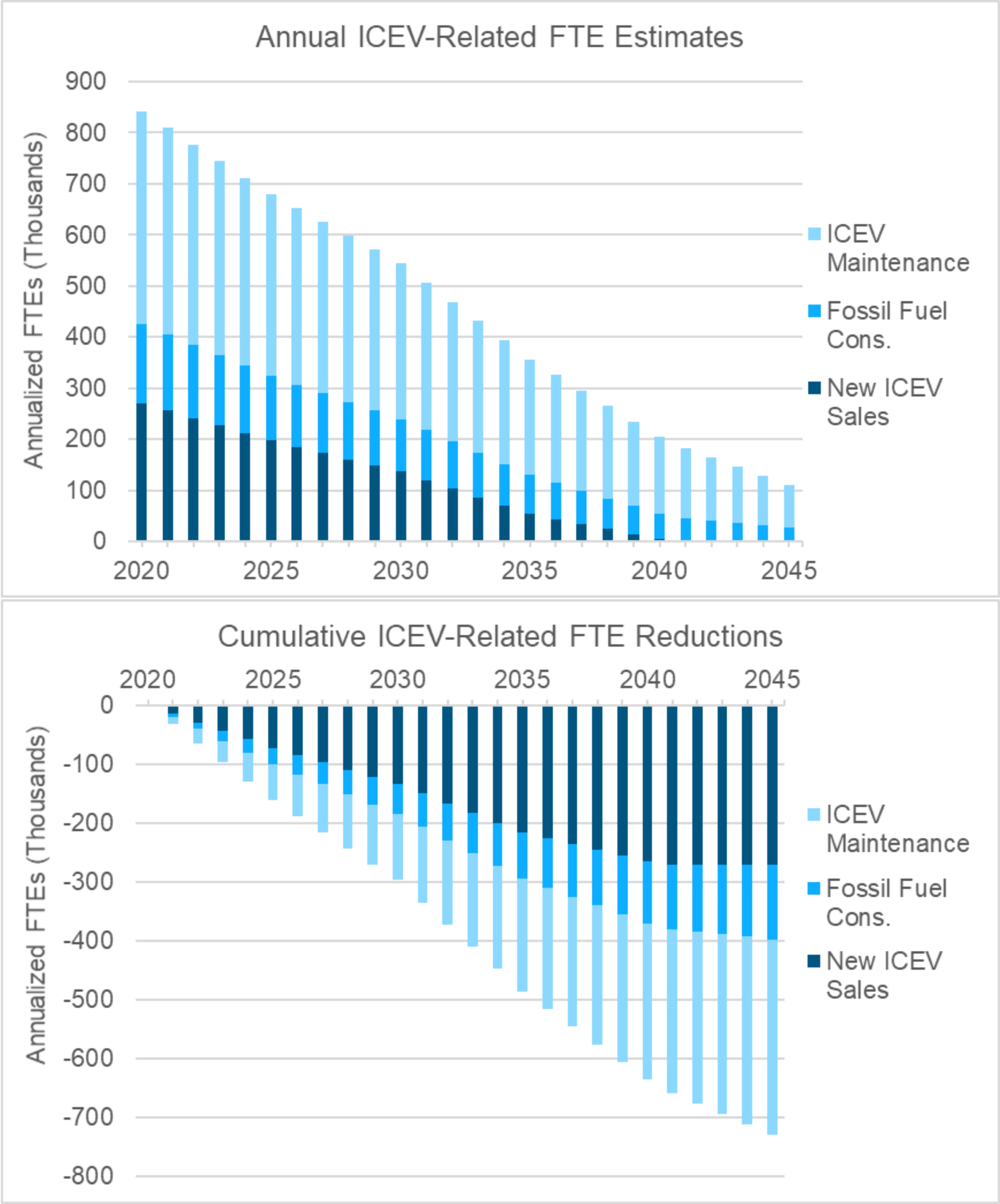


Figure 12.2. Projected estimates for annual total FTEs supported by ICEV-related industries (*top*) and (*bottom)* cumulative year-over-year FTE reductions resulting from contractions in these industries in California in thousands of FTEs by sector, 2020-2045

In conjunction, declining ICEV-related jobs and expanding numbers of ZEV-related jobs indicate a slight contraction in the transportation workforce between now and 2045, from over 800,000 FTEs in 2020 to slightly over 600,000 in 2045. Over 100,000 of these in 2045 are still linked to ICEV maintenance and fossil fuel consumption, reflecting the continued presence of millions of fossil fuel-burning vehicles in California's fleet. Two advantageous traits of ZEV technology are particularly important in driving this reduction:

- ZEVs incur **lower maintenance costs** than ICEVs across all major vehicle categories, substantially so in the case of LDVs—by far the largest vehicle class by number of vehicles. This translates to less spending on maintenance, and therefore fewer jobs related to maintenance.
- ZEVs are substantially **more fuel-efficient** than ICEVs, both now and in projected future years. ZEV owners and operators therefore spend less on fuel, leading to a contraction in the overall size of the fuels supply chain workforce. This trend is furthered by the lower labor intensity of electricity generation and distribution compared to extraction, refining, and distribution of fossil fuels.

12.5Sector-Specific Model Outputs and Policy Discussion

The overall figures presented above represent an amalgamation of our discrete, sector-specific model results. Below, we present these results and provide demographic and education and training profiles for the most impacted types of workers.[21] We then identify and address the most salient policy questions that arise from the results, accompanied by a discussion of policies likely to be helpful in assisting the transition for workers in both negatively and positively impacted industries.

1. **ICEV-Related Sectors**: jobs created through expenditures on new ICEV sales, fossil fuel consumption, and ICEV maintenance. This sector is unique among those considered in that it is anticipated to contract over the study period, rather than expand.
2. **EV-Related Sectors**: jobs created through expenditures on new BEV sales, electricity consumption for use as a transportation fuel, and BEV maintenance.
3. **FCEV-Related Sectors**: jobs created through expenditures on new FCEV sales, hydrogen fuel consumption, and FCEV maintenance.
4. **EVSE**: jobs created from expenditures on construction of new EV charging infrastructure and other EVSE installation.
5. **Hydrogen Refueling**: jobs created from expenditures on the construction of new hydrogen refueling stations.

12.5.1 Workforce Impacts Related to ICEV Sales, Fuels, and Maintenance

The reduction in usage of ICEVs and the commensurate drop in consumption of fossil fuels and ICEV maintenance services is expected to reduce annualized FTE employment in California from 841,914 FTEs in 2020

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[21] Education and training profiles are based on industry-wide, aggregated O*NET survey data. For an in-depth discussion of our utilization of this data, see the Technical Report.

to 111,165 in 2045, a drop of just over 730,000 FTEs (Figure 12.3).[22] Approximately 270,000 of these FTE job reductions between the bookend years are attributed to reduced sales of ICEVs, 127,000 to reduced consumption of fossil fuels, and 333,000 to lower demand for maintenance and repairs of ICEVs. Importantly, these figures include induced jobs—those supported by economic activity generated from these sectors but not necessarily directly linked to them. We predict continuous contraction at rates that are relatively steady within each sector, with the following highlights:

a. Total jobs related to **new ICEV sales** (Figure 12.3A) decline between approximately 9,000 to 17,000 FTEs per year until 2040, after which the lack of ICEV MDV and HDV sales leaves only a vestigial industry remaining. From its peak at more than 260,000 total FTEs in 2020, the industry falls below 50,000 in 2036 and is almost nonexistent in 2045.
b. Jobs related to **fossil fuel consumption** (Figure 12.3B) decline by approximately 4,000 to 6,000 FTEs per year for the entire study period. By 2045, fossil fuels for on-road vehicles continue to generate in excess of 25,000 FTEs, reflecting the continued presence of a greatly downsized but still substantial ICEV fleet on California's roads.
c. Jobs related to **ICEV maintenance** (Figure 12.3C) decline between approximately 10,000 and 14,000 FTEs per year over the entirety of the study period. Maintenance is the largest ICEV-related sector in terms of jobs over the course of the study, continuing to directly employ over 50,000 FTE workers and generate over 30,000 additional indirect and induced FTEs in 2045.

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[22] To estimate annual FTE figures for 2020-2045 we assign the mean FTE value for each modeled period to its midpoint year, then extrapolate FTE values for interim years assuming linear rates of contraction within each modeled period.

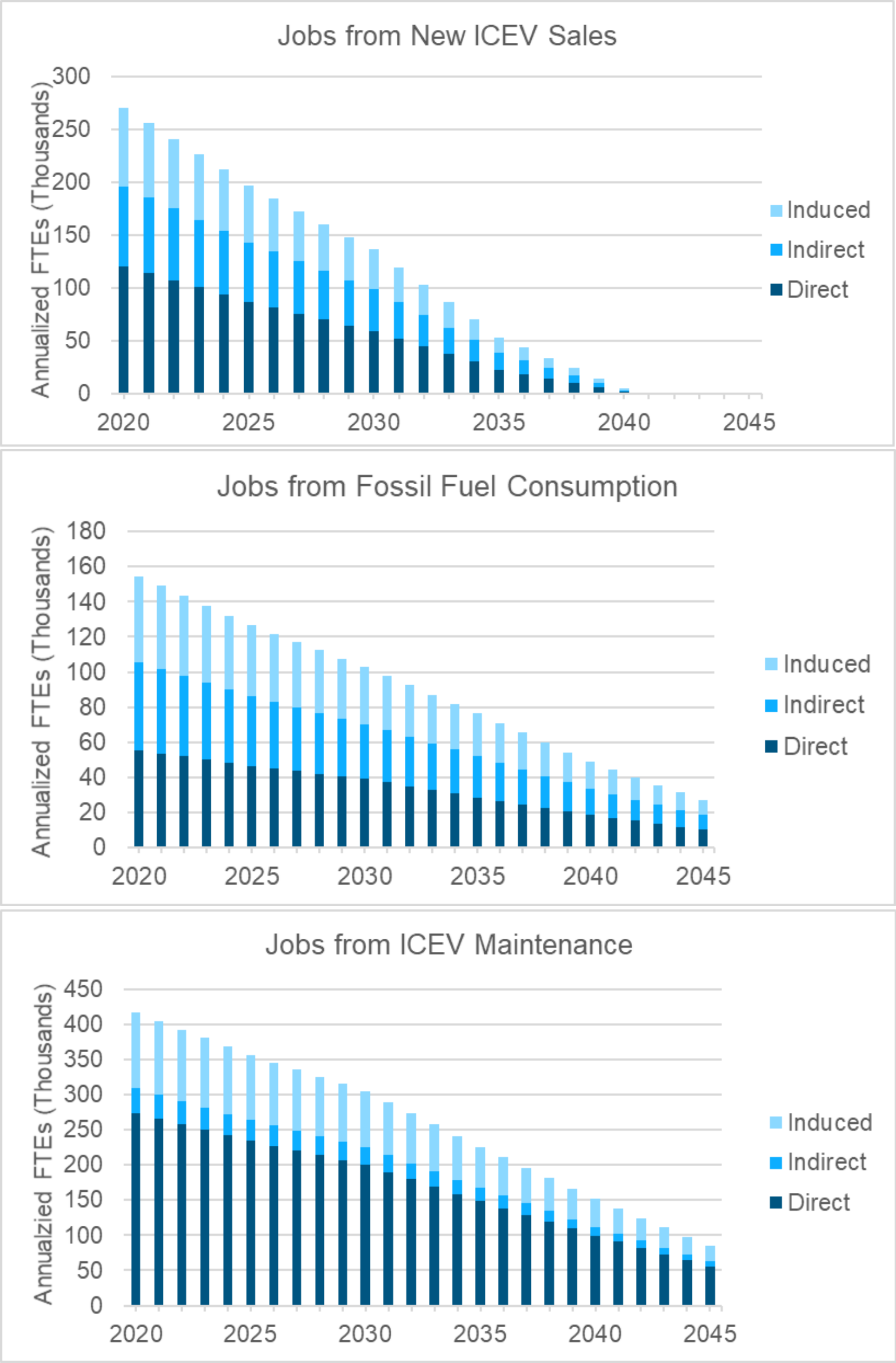

Figure 12.3. Projected estimates for annual direct, indirect, and induced jobs resulting from (*top*) new ICEV sales, (*middle*) fossil fuel consumption, and (*bottom*) ICEV maintenance in California in thousands of FTEs, 2020-2045.

12.5.1.1 Workforce Impacts at the Occupational Level

Table 12.1 shows the estimated FTEs for the top five occupations[23] within each ICEV-related sector in both 2020 and 2045, along with the calculated difference. The greatest reductions in annual FTEs occur for two occupations: 1) Vehicle and Mobile Equipment Mechanics, Installers, and Repairers, and 2) Retail Sales Workers. Reductions in new ICEV sales contribute to the declines in both these occupations, while reduced fossil fuel consumption and reduced ICEV maintenance contribute to lower numbers of sales workers and mechanics, respectively.

Table 12.1. Estimated direct and indirect annual FTEs in 2020 and 2045 and the calculated reduction for the top 5 occupations in each ICEV-related sector in California.

Rank	Occupation by Sector	Estimated Direct & Indirect Annual FTEs		
		2020	2045	Estimated Reduction 2020-2045
New ICEV Sales				
1	Retail Sales Workers	27,229.64	2.93	-27,226.71
2	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	23,072.88	2.49	-23,070.39
3	Motor Vehicle Operators	15,905.25	1.71	-15,903.54
4	Material Moving Workers	15,269.72	1.65	-15,268.07
5	Assemblers and Fabricators	11,059.58	1.19	-11,058.39
Fossil Fuel Consumption				
1	Retail Sales Workers	25,533.78	4,445.07	-21,088.71
2	Motor Vehicle Operators	6,629.18	1,154.05	-5,475.13
3	Material Moving Workers	6,047.13	1,052.72	-4,994.41

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[23] Top five occupations for each sector are determined by the five occupations with the greatest number of FTE job-years generated across the entire study period.

Rank	Occupation by Sector	Estimated Direct & Indirect Annual FTEs		
		2020	2045	Estimated Reduction 2020-2045
4	Sales Representatives, Wholesale & Manufacturing	4,738.13	824.84	-3,913.29
5	Supervisors of Sales Workers	3,934.18	684.89	-3,249.30
ICEV Maintenance				
1	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	156,115.18	31,545.00	-124,570.18
2	Other Office and Administrative Support Workers	15,955.38	3,223.98	-12,731.39
3	Supervisors of Installation, Maintenance, and Repair Workers	15,670.35	3,166.39	-12,503.97
4	Other Production Occupations	14,784.46	2,987.38	-11,797.08
5	Retail Sales Workers	13,523.64	2,732.62	-10,791.02

12.5.1.2 Workforce Impacts at the Industry Level

While the previous subsection focused on workforce changes in ICEV-related sectors at the occupational level, we now turn to industry-level analysis in order to provide further insight into how these reductions impact specific types of workers. The top five industries by FTE job-years (with some adjustments) for each ICEV-related sector are compared based on annualized FTE estimates for 2020 and 2045 (Table 12.2). Industry classifications are used here to allow for better alignment with the North American Industry Classification System (NAICS) and to capture workers whose specific occupations may represent a smaller magnitude of jobs, but whose industries are likely to experience acute contractions (e.g., fossil fuel-related industries).

Table 12.2. Declines in estimated annual FTEs in the top five affected industries in ICEV-related sectors between 2020 and 2045. The industries whose presence in the top five were driven overwhelmingly by induced jobs are not included. Additional industries outside of the top 5 are included in cases where direct or indirect employment effects are notably high.

Major Industry by Sector	Estimated Annual FTEs		
	2020	2045	Estimated Reduction 2020-2045
New ICEV Sales			
Retail - Motor vehicle and parts dealers	78,317.59	8.44	-78,309.15
Wholesale - Motor vehicle and motor vehicle parts and supplies	26,329.31	2.84	-26,326.47
Automobile manufacturing	12,255.58	1.32	-12,254.26
Truck transportation	7,109.65	0.77	-7,108.89
Other real estate	6,910.51	0.74	-6,909.77
Fossil Fuel Consumption			
Retail – Gasoline stores	36,117.14	6,287.48	-29,829.66
Wholesale electronics markets and agents and brokers	11,936.67	2,078.01	-9,858.67
Oil and gas extraction*	6,616.18	1,151.78	-5,464.39
Truck transportation	6,297.74	1,096.35	-5,201.39
Other real estate	3,959.95	689.37	-3,270.58
Warehousing and storage	3,768.00	655.96	-3,112.05
Wholesale – Petroleum and petroleum products*	3,603.07	627.24	-2,975.82
Petroleum refineries*	3,496.59	608.71	-2,887.89

Major Industry by Sector	Estimated Annual FTEs		
	2020	2045	Estimated Reduction 2020-2045
ICEV Maintenance			
Automotive repair and maintenance (except car washes)	275,990.51	55,767.30	-220,223.22
Other real estate	8,254.48	1,667.92	-6,586.56
Retail – Motor vehicle and parts dealers	4,401.32	889.34	-3,511.98
Retail – General merchandise stores	3,227.12	652.08	-2,575.04
Employment services	3,054.57	617.21	-2,437.36

*Percentile declines in fossil fuel-related industries reflect losses compared solely to jobs created from spending on gasoline and diesel for on-road vehicles in California and do not reflect other jobs in these industries driven by fossil fuel exports or consumption in other sectors like aviation and maritime transportation.

Across all three ICEV-related sectors, jobs related to automotive repair and maintenance see the most significant losses in overall magnitude—a reduction of approximately 181,000 annual FTEs between the two modeled periods. Retail sectors for both motor vehicles and parts and gasoline stations also undergo significant losses (approximately 69,000 and 23,000 FTEs, respectively). Wholesalers of motor vehicles and motor vehicle parts and supplies follow close behind with over 22,000 lost FTEs.

The greatest proportional declines occur in jobs related to sales of new ICEVs, as these halt before the end of the study period under the LC1 scenario. Industries related to fossil fuel consumption by on-road vehicles and ICEV maintenance are somewhat more persistent in 2045, losing between 70% and 80% of estimated annual FTEs. This reflects the fact that some ICEVs are expected to persist on the road for years after sales of new ICEVs drop to zero.

It is likely that the projected declines in employment pertaining to fossil fuel consumption will be ameliorated--at least to some small degree--by new opportunities in various biofuel-related sectors. However, given the relatively minor profile of such fuels in the LC1 scenario compared to electricity and hydrogen, our analysis does not attempt to quantify job gains in these sectors. Further study is called for to estimate potential job gains from expanding usage of biofuels.

12.5.2 Identifying and Describing Declining ICEV-Related Industries

Based on the data presented above, we focus our subsequent analysis on two groups of ICEV-related occupations where significant workforce declines are likely:

- Installation, maintenance, and repair occupations
- Motor vehicle parts wholesale and manufacturing

We identify the declining industries within California's fuel and vehicle supply chains below, using the naming used in U.S. Bureau of Labor Statistics (BLS) data, so that we may look at the current makeup of those industries to establish a baseline. We match installation, maintenance and repair occupations from the IMPLAN model with two industries: Automotive Mechanical and Electrical Repair and Maintenance, and Other Automotive Repair and Maintenance. We add the Motor Vehicle Parts Manufacturing industry to match with IMPLAN's motor vehicle parts wholesale and manufacturing projections.

A notable occupation that is not included among the declining occupations is retail workers for gasoline stations. There are two reasons for this exclusion: firstly, we have reason to believe that the IMPLAN model may be significantly undercounting job creation in analogous businesses for EV charging that would exhibit similarly low barriers to entry and geographic ubiquity (as explained above); and secondly, because developing a profile for such workers is limited by the lack of data that distinguishes between retail workers based on specific vendor types. For example, we have no way of distinguishing between a gas station worker and a cashier at a grocery store.

We must first understand how many workers are currently employed in impacted industries matched with IMPLAN model results. According to BLS data, an estimated total of 173,060 workers are currently employed in declining occupations. In the fuel supply chain, these occupations concern the extraction, manufacture, and distribution of fossil fuels. The estimated 75,740 workers in this category of occupations work in Oil and Gas Extraction, Petroleum and Coal Products Manufacturing, or their respective supportive industries: building and maintaining the infrastructure, operations, and technologies needed to support the fossil fuel economy. The majority of these workers (63%, 48,080 workers) can be found in Utility System Construction.

Declining occupations in the vehicle supply chain concern the manufacture and maintenance of vehicles that run on fossil fuels, especially any occupation concerning internal combustion engines or anything that pulls combustion out of an engine, such as exhaust or smog checks. An estimated 97,320 workers are employed in these industries.

Table 12.3. Estimated Employment and Wages for Declining Industries in California's Fuel and Vehicle Supply Chains

Industry	Employment	Annual Median Earnings
Oil and Gas Extraction	4,740	$87,880.00
Support Activities for Mining	10,050	$57,820.00
Utility System Construction	48,080	$61,390.00
Petroleum and Coal Products Manufacturing	12,870	$89,620.00
Fuel Subtotal	75,740	
Motor Vehicle Parts Manufacturing	12,580	$40,620.00
Automotive Mechanical and Electrical Repair and Maintenance	45,410	$43,400.00
Other Automotive Repair and Maintenance	39,330	$27,620.00
Vehicle Subtotal	97,320	
Total Employment	173,060	

Four major industries will likely experience a significant contraction due to the transition to net zero emissions. Employment and wage data for these industries can be seen in Table 12.3 above.

- Oil and Gas Extraction
- Support Activities for Mining
- Petroleum Refineries
- Automotive Repair and Maintenance

These industries fall under upstream and midstream operations in the fuel supply chain and contain occupations whose activities are directly linked to the consumption of fossil fuels in the state of California. Fossil fuel-dependent occupations within these industries will likely experience the greatest difficulty transitioning as their industries contract, due to the highly specialized nature of their skills. For example, non-fossil fuel related occupations, such as accountants and service managers, will likely find employment in a different industry. In contrast, oil derrick operators and petroleum pump system operators are unlikely to find employment beyond their industry since these occupations are specific to petroleum manufacturing. In Oil and Gas Extraction and Support Activities for Mining, key occupations—those that will both likely see employment declines and for whom transferability of industry-specific skills is challenging—include:

- Petroleum engineers (SOC code 17-2171)
- Service unit operators for oil and gas (SOC code 47-5013)
- Oil derrick operators (SOC code 47-5011)
- Wellhead pumpers (SOC code 53-7073)
- Unskilled laborers engaged in daily field operations (roustabouts) (SOC code 47-5071)
- Petroleum pump system operators (SOC code 51-8093)

The combined employment from these occupations accounts for approximately 29% (4,340) of total employment in these industries (14,790).

Regarding the Petroleum Refineries industry, key occupations are similar to those in extraction and mining support, with petroleum engineers and petroleum pump system operators making up the highest occupational employment in the industry (4,410 workers representing 34.27% of the industry employment).

As seen previously in Table 12.2, the annualized FTE impact in these industries will be approximately 5,464 in Oil and Gas Extraction, approximately 2,888 in Petroleum Refineries, and approximately 220,000 in Automotive Repair and Maintenance. Of note, the industries in the IMPLAN model do not match exactly with the industry classifications in BLS data. This means that in some cases, figures related to certain fields of employment (such as Automotive Repair and Maintenance) produced by the model appear to be greater in magnitude than their closest baseline categorical counterpart, due to inclusion of a broader array of workers within that number. This is because IMPLAN accounts for jobs in particular fields that are not captured within BLS surveys.

Also worth reiterating, the model estimates employment related to Automotive Repair and Maintenance based on expenditures derived from fleet size, vehicle miles traveled (VMT), and per-mile maintenance cost. Unpaid, non-professional maintenance performed on a vehicle by the owner would be reflected in IMPLAN's job totals while not appearing in BLS data. Additionally, the IMPLAN model estimates are FTEs, representing the number of people working full-time over the enumerated time periods. This could mean one person working full-time for all of those years, or five people each working one year full-time.

12.5.2.1 Demographic Exploration of Declining ICEV-Related Industries

The declining ICEV-related industries in California all have similar demographics, since these industries fall under the upstream and midstream operations of the fuel supply chain. We focus on three demographic characteristics: race, ethnicity, and gender. Including these demographics allows us to account for how the contraction of the fossil fuel industries will impact different workers. Table 12.4 provides demographic percentages for each declining industry.

Table 12.4. Demographic Profile of Declining Industries

Demographic Group	Oil and Gas Extraction	Support Activities for Mining	Petroleum Refineries	Automotive Repair and Maintenance
Ethnicity				
Hispanic or Latino	78.64%	54.88%	74.57%	55.38%
Not Hispanic or Latino	21.36%	45.12%	25.43%	44.62%
Race				
White	82.23%	86.71%	75.03%	78.77%
Black or African American	4.51%	4.52%	7.42%	4.61%
American Indian and Alaska Native	0.91%	2.19%	1.08%	1.87%
Asian	9.45%	3.59%	12.54%	10.88%
Native Hawaiian/Other Pacific Islander	0.48%	0.56%	0.77%	0.66%
Two or More	2.42%	2.42%	3.16%	3.22%
Sex				
Female	24.66%	12.15%	19.41%	23.86%
Male	75.34%	87.85%	80.59%	76.14%
Age				
14–18 years	N/A	0.13%	0.06%	1.49%
19–21 years	0.30%	1.67%	0.51%	4.48%
22–24 years	0.97%	4.04%	1.47%	5.88%
25–34 years	16.35%	26.86%	16.87%	21.70%
35–44 years	26.50%	30.04%	26.43%	21.05%
45–54 years	22.34%	19.15%	25.55%	20.58%
55–64 years	27.33%	13.74%	24.62%	17.20%
65–99 years	6.23%	4.38%	4.49%	7.62%

Most workers in declining industries report Hispanic and Latino ethnicity. The highest concentration of Hispanic and Latino workers is in Oil and Gas Extraction (78.64%), followed by Petroleum Refineries (74.57%), then Automotive Repair and Maintenance (55.38%); and the lowest concentration is in Support Activities for Mining (54.88%).

Across all declining industries, workers are predominantly White, with the lowest concentration in Petroleum Refineries (75.03%) and the highest concentration in Support Activities for Mining (86.71%). White as a racial demographic is marked separately from Hispanic or Latino as an ethnic identity. While we do not know how many workers who identify as Hispanic or Latino in terms of ethnic identity also identify as White (or non-White) in terms of racial identity, we can assume there is overlap.

The only other racial group to attain double-digit percentages is Asian, which reaches a maximum of 12.54% for Petroleum Refineries, followed by 10.88% for Automotive Repair and Maintenance. The percentage of workers who report Asian race are low in Oil and Gas Extraction (9.45%) and Support Activities for Mining (4.52%).

Worker sex is highly skewed across all industries, with men accounting for 75.34% of employment in Oil and Gas Extraction, 76.14% of employment in Automotive Repair and Maintenance, 80.59% of employment in Petroleum refineries, and 87.85% of employment in Support Activities for Mining.

Finally, worker age is highly concentrated across four consecutive age groups: 25–34, 35–44, 45–54, and 55–64 years. Petroleum Refineries and Support Activities for Mining both have the highest concentration of workers in the 35–44 year age range. While Oil and Gas Extraction does have a high percentage of this age group, most workers in this industry are in the 55–64 year age range.

12.5.2.2 Industry Geography

The geographic placement of some declining industries is somewhat limited to a few counties in California, while others (such as Automotive Repair and Maintenance) are distributed throughout. The highest concentration of extraction is in Kern County, where oil and gas extraction operations employed 1,770 workers in 2019 (almost 40% of total industry employment in 2019), with remaining extraction-related employment mostly concentrated in Southern California and the Central Coast region. Two counties dominate refining employment: Contra Costa County (4,423 workers in 2019) and Los Angeles County (4,631 workers in 2019). These two counties accounted for an overwhelming majority of employment in the petroleum refinery industry (83.53% of total industry employment) with Kern County and Orange County accounting for the remaining employment, with 629 workers and 75 workers, respectively.[24]

12.5.2.3 Education and Training Profile for Declining ICEV-Related Occupations

We examine the trends in education and training requirements for declining ICEV-related occupations (and for the expanding BEV-related occupations in the following subsection) by type of education or training, and by supply chain.[25] These data represent aggregated, industry-wide data and are meant to establish high-level

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[24] Additional refineries are in operation in Santa Barbara County and Solano County. However, Quarterly Census of Employment and Wages does not have 2019 estimates for petroleum refinery employment for these counties.

[25] As mentioned, education and training profiles rely on survey data from O*NET. For more information on O*NET, our methodology for using data therefrom, and a more robust presentation of said data, see the Technical Report.

trends in the affected workforce. More robust analysis at the occupation level is both possible and recommended as the state begins to manage the transition to ZEVs and develops strategies targeting specific types of workers.

The majority of impacted workers in declining ICEV-related occupations require only a High School Diploma or less to do the job. This applies to approximately 26% in the fuel supply chain and 46.4% in the vehicle supply chain, making up a combined 72.5% of employees in the declining ICEV-related occupations. In the fuel supply chain, a small, but not insignificant, minority of impacted workers require some additional post-secondary certificate (9.7%).

The plurality of workers in the vehicle supply chain need either 1–3 months of related work experience or 1–2 years of related work experience (23% and 21.1%, respectively). The fuel supply chain is much more centrally distributed, with the majority of workers needing somewhere between 3 months to 4 years of training. 12.3%, need 3–6 months of related work experience, with incrementally smaller and smaller percentages of employees needing additional amounts of related work experience.

Very few employees in either supply chain need more than one year of either on-the-job training or in-plant (classroom style) training. The majority of fuel supply chain workers require anywhere from one month to one year of either on-the-job or in-plant training. Most vehicle supply chain workers also require anywhere from one month to one year of on-the-job training, but unlike fuel supply chain workers, they skew heavily toward requiring less of it. A combined 49.4% of them will need up to 6 months, with only 5% of them requiring 6-12 months. They require much less in-plant training as well. Most either need only up to one month of in-plant training (23.7%) or 3-6 months (22.6%).

All of this points to a landscape in which the workers who lose their jobs due to California's transition to ZEVs are in occupations that mostly do not require any college education, where most of the technical skills can be learned on the job in less than a year.

12.5.3 Workforce Impacts Related to BEV Sales, Fuels, and Maintenance

The adoption of BEVs is projected to create over 4.8 million FTE job-years in California over the next 25 years through labor related to the sales of new BEVs, consumption of electricity as a transportation fuel, and maintenance for BEVs. A significant majority of these are derived from expanding numbers of new BEV sales, which account for over 3.5 million FTE job-years. Over 370,000 FTE job-years—nearly two-thirds of them induced—arise from consumption of electricity for transportation. Maintenance of BEVs accounts for over 883,000 FTE job-years.

To estimate FTEs in each year from 2020 to 2045, we assign the mean annual FTE value for each modeled 5–6 year increment to the chronological midpoint of that period, then extrapolate FTE values for other years assuming a linear rate of job growth within each period (Figure 12.4). We predict continuous growth in jobs across all three BEV-related sectors over the entire study period, with the following highlights:

a. Annual **new BEV sales FTEs** (Figure 12.4A) are predicted to go through two pronounced periods of expansion. By 2025 annual FTEs are expected to exceed 87,000, after which job growth is modest through 2030. From 2031 to 2035, annual FTEs once again rise quickly, reaching nearly 190,000 FTEs in 2035. Minor growth continues thereafter, with annual FTEs in 2045 exceeding 200,000.

b. Annual **electricity consumption for transportation FTEs** (Figure 12.4B) see relatively little growth through 2030, exceeding 5,000 FTEs for the first time in 2029. Growth accelerates slightly after 2030, with consistent year-over-year growth of a few thousand FTEs. Annual FTEs related to this sector exceed 38,000 in 2045. The most concentrated area of job growth in this sector is within the solar electric power generation industry.

c. Annual **BEV maintenance FTEs** (Figure 12.4C) follow a growth pattern similar to that for jobs related to electricity consumption for transportation, albeit at a greater magnitude. Annual FTEs in this sector first exceed 10,000 in 2027. After 2030, year-over-year growth is consistently a few thousand FTEs per year, such that the sector accounts for over 83,000 FTEs in 2045.

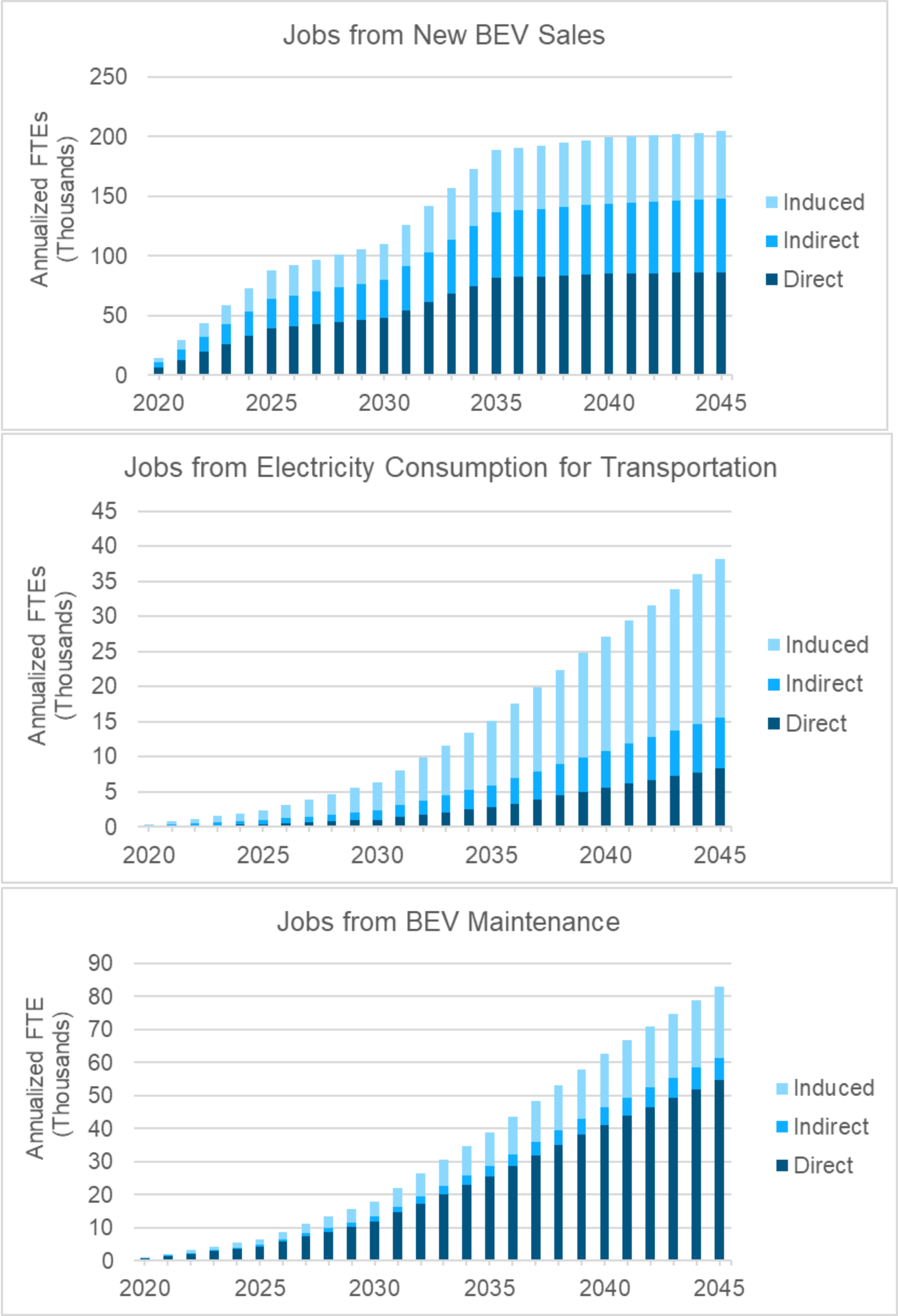

Figure 12.4. Projected estimates for annual direct, indirect, and induced jobs resulting from (*top*) new BEV sales, (*middle*) consumption of electricity for transportation, and (*bottom*) BEV maintenance in California in thousands of FTEs, 2020-2045.

12.5.3.1 Workforce Impacts at the Occupational Level

The five highest-employment occupations for each BEV-related sector are shown in Table 12.5 below. We provide figures for both the total FTE job-years realized across the entire study period and an estimate of FTEs realized for each in 2045. The scale of job growth created by new BEV sales is sufficiently large that all occupational growth from the other two BEV-related sectors is overshadowed by occupations related to the first, even outside of the top 5 (with the exception of mechanics, installers, and repairers involved in BEV maintenance). See the Technical Report for a more in-depth overview of projected job growth by occupation.

Table 12.5. Top 5 occupations by total FTE job-years resulting from expenditures on new BEV sales, electricity consumption for transportation, and BEV maintenance, respectively, in California, 2020-2045.

Rank	Occupation	FTE Job-Years, 2020-2045	Estimated FTEs, 2045
New BEV Sales			
1	Retail Sales Workers	347,609.15	19,824.73
2	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	296,001.41	16,881.46
3	Motor Vehicle Operators	209,309.92	11,937.30
4	Material Moving Workers	201,043.72	11,465.86
5	Assemblers and Fabricators	160,779.40	9,169.52
Electricity Consumption for Transportation			
1	Construction Trades Workers	14,985.64	1,544.78
2	Business Operations Specialists	12,569.16	1,295.68
3	Other Installation, Maintenance, and Repair Occupations	10,812.14	1,114.56
4	Engineers	9,407.98	969.81
5	Top Executives	6,165.09	639.46
BEV Maintenance			
1	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	330,851.10	31,105.01
2	Other Office and Administrative Support Workers	33,813.84	3,179.01
3	Supervisors of Installation, Maintenance, and Repair Workers	33,209.80	3,122.22
4	Other Production Occupations	31,332.12	2,945.69
5	Retail Sales Workers	28,660.25	2,694.50

12.5.4 Identifying and Describing Expanding BEV-Related Industries

In order to place IMPLAN's predictions within the context of current BLS data, we look at industries in the transportation sector that are responsible for generating and distributing the electricity for BEVs, and will therefore benefit from this transition. Table 12.6 outlines expanding industries, which currently employ an estimated 145,330 workers.

All of the expanding BEV-related occupations in the fuel supply chain concern electric power generation, transmission, and distribution, and their supportive industries. The vast majority (76%, 110,290 workers) are electrical contractors.

Table 12.6. Estimated Employment and Wages for Expanding Industries in California's Fuel Supply Chain

Industry	Employment	Annual Median Earnings
Electric Power Generation, Transmission, and Distribution	18,200	$100,100.00
Power and Communication Line and Related Structures Construction	16,860	$63,730.00
Electrical Contractors and Other Wiring Installation Contractors	110,290	$60,550.00
Total Employment	145,350	

Currently, EV consumption of electricity accounts for 0.68% of total electricity consumed in the state. To accommodate the increased demand of electricity by EVs, two specific industries will likely grow: Electric Power Generation, Transmission, and Distribution; and Electrical and Wiring Contractors. The latter industry is responsible for the installation of electric vehicle charging stations, which are provided by a manufacturer.

While each of these industries encompass a variety of occupations, certain occupations are directly linked to upgrading infrastructure and increasing output for increased voltage consumption. In addition to power generation and transmission, end-user consumption infrastructure (i.e., charging station installation) will require more electricians, as manufacturers often contract out charging station installation to local electricians. Key occupations—in this context, those likely to exhibit significant growth—for each industry are shown below:

- Electric Power Generation, Transmission, and Distribution
    - Electricians (SOC code 47-2111)
    - Solar Photovoltaic Installers (SOC code 47-2231)
    - Electrical and Electronics Repairers (SOC code 49-2094)
    - Wind Turbine Service Technicians (SOC code 49-9081)
    - Power Plant Operators (SOC code 51-8013)
- Electrical and Wiring Contractors
    - Construction Laborers (SOC code 47-2061)
    - Electricians (SOC code 47-2111)
    - Solar Photovoltaic Installers (SOC code 47-2231)
    - Helpers Electricians (SOC code 47-3013)

The combined worker estimates for key occupations in the Electric Power Generation, Transmission, and Distribution industry represent 14.64% (2,670 workers) of total industry employment (18,239 workers in 2019). This is substantially lower than the key occupation counts from the declining industries. Conversely, key occupations in Electrical and Wiring Contractors account for 55.63% (62,630 workers) of industry employment in 2019 (112,583).

12.5.4.1 Demographic Profile of Expanding BEV-Related Sectors

The demographic profiles of the growing industries are similar, with race, ethnic, and sex percentages aligning across both industries. We include growing industry demographics to account for any existing demographic disparities in these industries. Table 12.7 lists the demographic profiles of the two growing industries.

Table 12.7. Demographic Profile of Growing Industries

Demographic Group	Electric Power Generation, Transmission, and Distribution	Electrical and Wiring Contractors
Ethnicity		
Hispanic or Latino	67.55%	60.40%
Not Hispanic or Latino	32.45%	39.60%
Race		
White	73.28%	83.71%
Black or African American	8.86%	4.31%
American Indian and Alaska Native	1.44%	1.79%
Asian	12.99%	6.33%
Native Hawaiian/Other Pacific Islander	0.42%	0.65%
Two or More	3.02%	3.22%
Sex		
Female	26.05%	17.58%
Male	73.95%	82.42%
Age		
14–18 years	0.16%	0.49%
19–21 years	0.47%	2.59%
22–24 years	1.57%	5.14%
25–34 years	15.36%	25.35%
35–44 years	28.01%	26.75%
45–54 years	26.77%	20.44%
55–64 years	22.97%	14.34%
65–99 years	4.68%	4.90%

Worker ethnicity is predominantly Hispanic or Latino, with 60.40% or workers in the electrical contractor industry and 67.55% of workers in power generation, transmission, and distribution reporting this ethnicity.

As in the declining industries, workers in both growing industries are majority White: 73.28% for Electric Power Generation, Transmission, and Distribution, and 83.71% for Electrical and Wiring Contractors. Asian workers are the next highest represented group, with 12.99% in power generation and 6.33% in the electrical contractor industry. No other racial group reaches double-digit percentages.

Regarding worker sex, workers are overwhelming male: 73.95% in power generation, transmission, and distribution, and 82.42% in the electrical contractor industry.

Across both industries, most workers fall within the 25–64 year age range. Workers in power generation, transmission, and distribution tend to be older, with the highest concentration of workers age 35–44 years (28.01%), followed by workers age 45–54 years (26.77%) and 55–64 years (22.97%). Conversely, electrical and wiring contractors have a higher concentration of younger workers, with the highest percentage 35–44 years (26.75%), followed by 25–34 years (25.35%), and 45–54 years (20.44%).

12.5.4.2 Industry Geography

Unlike the declining industries, the growing industries are not geographically distinct, as power plants and transmission lines are spread across the entire state (California Energy Commission, 2020a, 2020b). Similarly, electric vehicle charging stations will be dispersed across the entire state in a manner akin to gasoline stations. However, the bulk of growth of these industries is likely to occur initially in areas where EV usage is already rising, such as California's major urban centers, especially since infrastructure developments are a large financial undertaking.

12.5.4.3 Education and Training Profile for Expanding BEV-Related Occupations

We will now examine the trends in education and training requirements for growing occupations by type of education or training and by supply chain, using the same variables used above. Since there are no growing vehicle supply chain occupations, all of the graphs represent percentages solely for the fuel supply chain.

Most workers (63.2%) in expanding BEV-related occupations currently only need some post-secondary certificate to be able to get their job. While some workers in expanding BEV-related occupations need between 3 months to 2 years of related work experience (a combined 36%), most need more; 54% need 2–4 years of related work experience.

Approximately half of workers in expanding occupations require up to one year of on-the job training (a combined 53%), with the remaining half requiring 1–2 years (45.4%). Similarly, approximately half of the workers (at 54.9%) need 6–12 months of classroom training provided by their employer, while the remaining half (45.1%) require 6 months or less.

California has already taken many steps in ensuring access to high-quality job pipelines for frontline and vulnerable communities through the implementation of its High Road Training Partnerships (HRTP) and High Road Construction Careers (HRCC) programs, and has learned much about industry-led problem solving, the prioritization of partnerships over programs, and the incorporation of worker voice and expertise in ensuring equitable jobs in managing climate change [370]. Further models and design elements are discussed below.

Additionally, for an example of further analysis that can be done using O*NET data, see the Technical Report. We provide an example of how the state may use the O*NET Related Occupations Matrices (ROM) to anticipate and therefore help facilitate key workforce transitions. While the data are not perfect, the analysis can help gain some purely **descriptive**, rather than **prescriptive**, information.

12.5.5 Workforce Impacts Related to Hydrogen Vehicles, Fuels, and Maintenance

The adoption of hydrogen FCEVs is expected to create over 1.5 billion FTE job-years in California over the next 25 years through labor related to the sales of new FCEVs, hydrogen fuel consumption, and maintenance for FCEVs. Approximately 430,000 of these FTE job-years come as a result of vehicle sales, 474,000 from fuel consumption, and nearly 688,000 from maintenance.

Each category's created jobs include a single outlier industry that constitutes a majority of its created direct jobs and is therefore the modal industry for job creation within each sector. In FCEV sales, this industry is Retail Motor Vehicle and Parts Dealers (nearly 104,000 FTE job-years). Retail Fuel Stores constitute most direct jobs related to hydrogen fuel consumption (nearly 174,000 FTE job-years). The entirety of direct jobs created from FCEV maintenance are predicted to be within Automotive Repair and Maintenance.

To estimate FTEs in each year from 2021-2045 we assign the mean FTE value for each 5-year increment to the midpoint year of that period, then extrapolate FTE values for other years, assuming a linear rate of growth across each 5-year period (Figure 12.5). We predict continuous year-over-year increases for the entire study period in jobs related to all three sectors, with the following highlights:

a. Annual **FCEV Vehicle Sales FTEs** (Figure 12.5A) first break 5,000 in 2026 and expand at a pace of a few thousand per year until 2040, after which growth slows somewhat. FTEs from this sector sit just above 30,000 in 2045.
b. Annual **Hydrogen Fuel Consumption FTEs** (Figure 12.5B) exceed 5,000 for the first time in 2027, and then year-over-year growth accelerates slightly to between 3,000 and 6,000 FTEs for the remainder of the study period. FTEs from this sector exceed 43,000 in 2045.
c. Annual **FCEV Maintenance FTEs** (Figure 12.5C) are similar in scale to the other two hydrogen-related sectors before 2030, breaking 5,000 in 2027. However, growth in FTEs resulting from activity in this sector outstrips growth in the other two hydrogen-related sectors after 2030. FCEV Maintenance FTEs are projected to reach nearly 30,000 in 2035, and close to 70,000 in 2045.

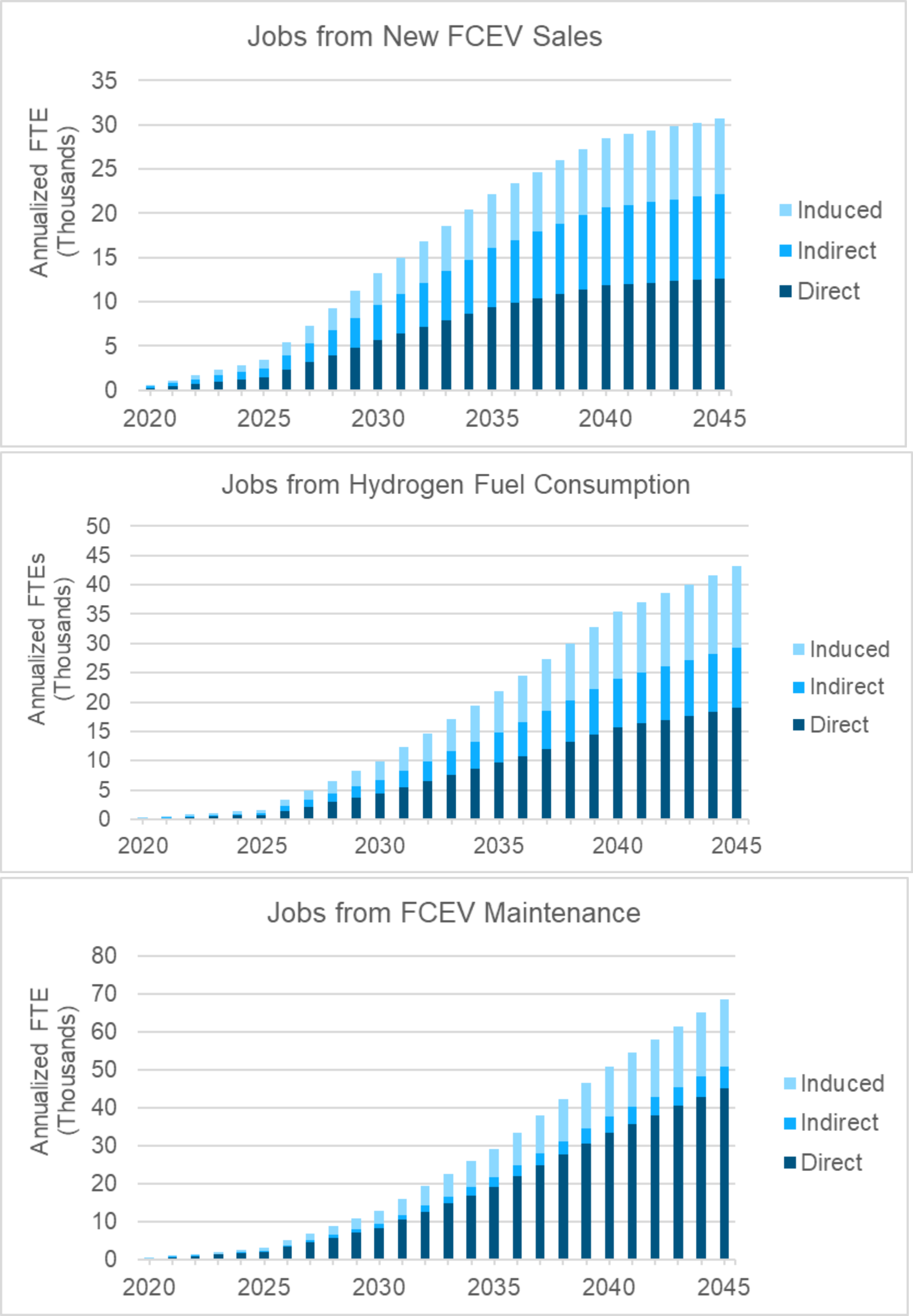

Figure 12.5. Projected estimates for annual direct, indirect, and induced jobs resulting from (*top*) new FCEV sales, (*middle*) hydrogen fuel consumption, and (*bottom*) FCEV maintenance, in California in thousands of FTEs, 2021-2045.

12.5.5.1 Workforce Impacts at the Occupational Level

Table 12.8 shows FTE job-years realized for the top five occupations within each FCEV-related sector across the entire study period. Retail Sales Workers and Vehicle and Mobile Equipment Mechanics, Installers, and Repairers make up a significantly greater number of the FTE job-years generated over the 25-year study period than other occupations across the three FCEV-related sectors. Retail Sales Workers are the largest occupation by FTE job-years in both the new FCEV sales sector (37,261) and the hydrogen fuel consumption sector (120,879), while also being the fifth-largest occupation in the FCEV maintenance sector (22,315). Vehicle and Mobile Equipment Mechanics, Installers, and Repairers are the most heavily represented occupation by far within the FCEV maintenance sector by FTE job-years (257,596) and the second-most common in the new FCEV sales sector (32,112).

Table 12.8. Top 5 occupations by total FTE job-years resulting from expenditures on new FCEV sales, hydrogen fuel consumption, and FCEV maintenance, respectively, in California, 2021-2045.

Rank	Occupation by Sector	FTE Job-Years, 2020-2045
New FCEV Sales		
1	Retail Sales Workers	37,260.53
2	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	32,112.05
3	Assemblers and Fabricators	26,273.57
4	Motor Vehicle Operators	23,806.40
5	Material Moving Workers	23,298.12
Hydrogen Fuel Consumption		
1	Retail Sales Workers	120,878.60
2	Supervisors of Sales Workers	17,576.35
3	Material Moving Workers	16,738.57
4	Motor Vehicle Operators	13,181.11
5	Food and Beverage Serving Workers	11,623.49
FCEV Maintenance		
1	Vehicle and Mobile Equipment Mechanics, Installers, and Repairers	257,595.96
2	Other Office and Administrative Support Workers	26,326.98
3	Supervisors of Installation, Maintenance, and Repair Workers	25,856.67
4	Other Production Occupations	24,394.87
5	Retail Sales Workers	22,314.51

12.5.6 Workforce Impacts Related to EVSE Infrastructure Construction and Installation

Construction of EV charging infrastructure and installation of new EVSE is expected to create over 805,000 FTE job-years over the next 25 years. This translates to an average of slightly over 32,000 full-time jobs across the entire time period. A majority of these—over 460,000 FTE job-years—are directly created, predominantly through jobs associated with the construction of new commercial buildings. Nearly 134,000 FTE job-years are created indirectly across myriad industries, and over 211,000 FTE job-years are induced.

We estimate FTEs in each year from 2021-2045 by allocating the 5-year increment job figures based on spending patterns within each period (Figure 12.6). The resulting figures show a relatively modest job market (between 5,000 and 7,000 FTEs) where EVSE is concerned before 2025, after which growth quickly accelerates. FTEs in 2026 are expected to be nearly double those in 2025, driven by a pronounced ramp-up in expenditures on new EVSE installation and infrastructure construction. The sector is projected to continue adding multiple thousands of FTEs nearly every year until the peak in 2039, after which FTEs begin to fall as the pace of new EVSE installation and infrastructure construction slows.

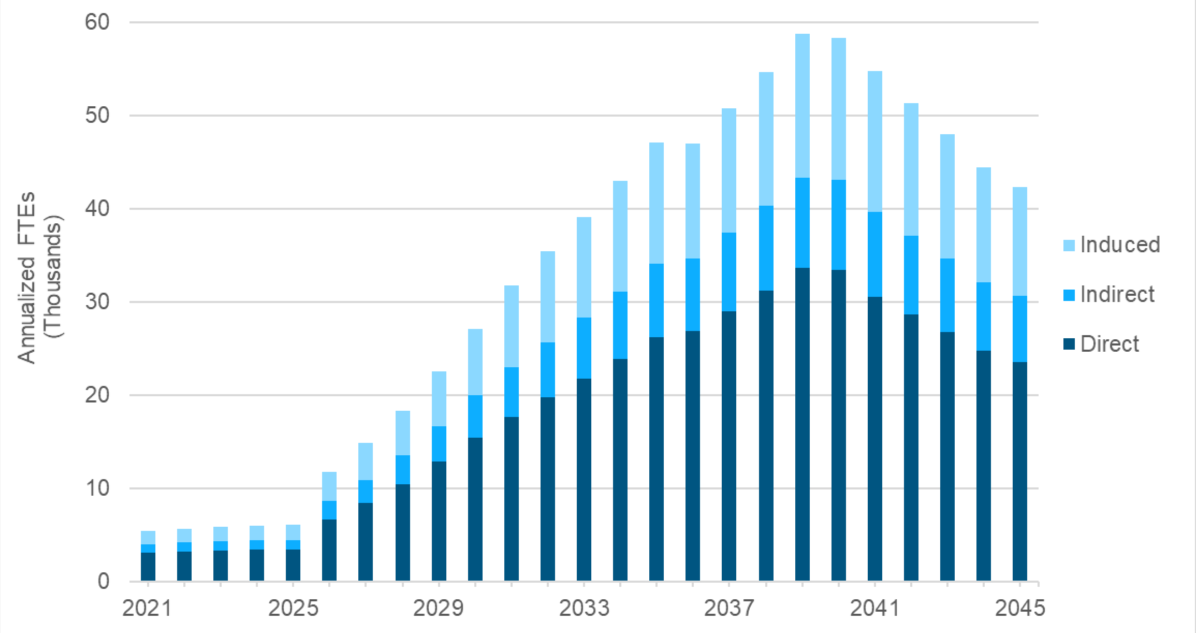

Figure 12.6 Projected estimates for annual direct, indirect, and induced jobs resulting from EV charging infrastructure construction and other EVSE installation in thousands of FTEs, 2021-2045.

12.5.6.1 Workforce Impacts at the Occupational Level

Table 12.9 shows the top five occupations related to EV charging infrastructure construction and new EVSE installation in terms of total realized FTE job-years across the study period. We project the greatest number of FTE job-years, by far, among Construction Trades Workers (nearly 209,000 FTE job-years between 2021 and 2045). This reflects the labor-intensive nature of contractor labor for construction of new EV charging infrastructure. The remaining occupations within the top five by FTE job-years across the 25 year period are Other Installation, Maintenance, and Repair Occupations (30,488), Supervisors of Construction and Extraction Workers (26,134), Motor Vehicle Operators (23,491), and Other Office and Administrative Support Workers (20,066).

Table 12.9. Top 5 occupations related to EV charging infrastructure construction and other EVSE installation by FTE job-years, 2021-2045.

Rank	Occupation	FTE Job-Years, 2021-2045
1	Construction Trades Workers	208,708.33
2	Other Installation, Maintenance, and Repair Occupations	30,488.02
3	Supervisors of Construction and Extraction Workers	26,133.91
4	Motor Vehicle Operators	23,490.93
5	Other Office and Administrative Support Workers	20,066.24

12.5.7 Workforce Impacts Related to Hydrogen Refueling Infrastructure

Construction of new hydrogen refueling infrastructure is expected to create nearly 92,000 FTE job-years between 2021 and 2045, which translates to nearly 3,700 average annual FTEs. The two most prominent industries in this sector are Architectural, Engineering, and Related Services (20,725 FTE job-years) and Construction of New Commercial Structures (10,993 FTE job-years).

As with EVSE, above, we estimate FTEs in each year from 2021-2045 by allocating the 5-year increment job figures based on spending patterns within each period (Figure 12.7). Projections once again indicate relatively modest job growth up to 2025, with FTEs in any given year not exceeding 1,000 during this period. A period of significant job growth begins in 2026 and continues until the peak year of 2040, when total FTEs reach 7,000. As new construction begins to slow in 2041, FTEs in each year fall abruptly to just over 5,000 in that year, with slight annual declines thereafter. FTEs in 2045 sit at roughly 4,000.

Overall, this pattern of workforce impacts is similar to that of EVSE but at a reduced magnitude that reflects the smaller profile of FCEVs versus BEVs in the California fleet.

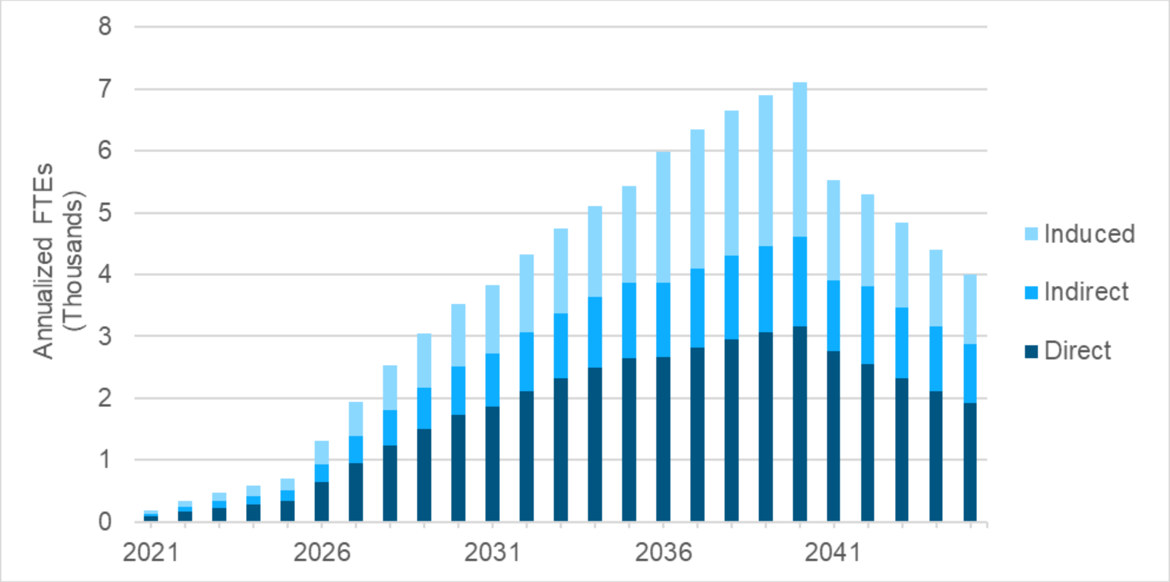

Figure 12.7 Projected estimates for annual direct, indirect, and induced job creation from hydrogen refueling infrastructure construction in thousands of FTEs, 2021-2045.

12.5.7.1 Workforce Impacts at the Occupational Level

Table 12.10 showcases the top five employing occupations in the hydrogen refueling infrastructure sector by FTE job-years realized over the entire study period. The data indicate that Construction Trades Workers constitute the largest category by FTE job-years (10,320) over the 25-year period, as was the case with EVSE. Engineers (5,920), Drafters, Engineering Technicians, and Mapping Technicians (3,428), Business Operations Specialists (2,903), and Motor Vehicle Operators (2,655) round out the top five occupations. Outside of the three most high-profile occupations, we see few standout areas of concentrated employment related to hydrogen refueling infrastructure construction.

Table 12.10. Top 5 occupations by FTE job-years created from expenditures on new hydrogen refueling station construction in California, 2021-2045.

Rank	Occupation	FTE Job-Years, 2021-2045
1	Construction Trades Workers	10,320.09
2	Engineers	5,920.15
3	Drafters, Engineering Technicians, and Mapping Technicians	3,427.96
4	Business Operations Specialists	2,903.18
5	Motor Vehicle Operators	2,654.82

12.6Conclusion

The profile of highly impacted industries and workers presented above—those in declining ICEV-related sectors and growing ZEV-related sectors—suggest a few key policy questions for the state to consider going forward:

- How might the state protect workers in declining industries during an unpredictable and disruptive transition to ZEVs?
- What are efficacious strategies for the state to support the transition of workers in declining industries, given the significant uncertainties and high variability of conditions across geographies and demographic groups?
- What are the best models and design elements to ensure that frontline and vulnerable communities continue to have access to apprenticeship programs that lead to quality careers, and how might the state grow upon what it is already doing in that area?
- How might the state ensure that employers, especially those who receive public tax dollars and incentives in this transition, commit to providing high-quality jobs, and are held accountable to those commitments?

Much of California's transition to ZEVs will happen by "greening" many existing occupations, rather than creating new, niche "green" occupations [371]. This presents the state with a golden opportunity to create not only new, high-quality jobs, but to also ensure that many existing industries and occupations transition to better practices.

Without a cohesive vision and guidance from the state level, there is a risk that California will exacerbate negative labor market trends as it pursues its climate goals. A scenario in which the state depends on low-wage, low-security jobs to decarbonize its transportation sector would be an undesirable outcome.

California has already taken many steps in ensuring robust economic development policies for frontline and vulnerable communities. It now has the opportunity to expand on these practices to manage the complex task of moving the entire transportation sector to zero-emissions and make systemic changes that will have sustainable and long-lasting impacts reducing barriers to full-time employment across the state.

This report has shown that while data are useful in helping to identify certain problems, it do not point to exact solutions, because they may be incomplete and may require some assumptions needed to perform the analysis. Additionally, the significant job growth our study predicts will present many unique scenarios depending on locality, industry, and timing, as many key players release and respond to Requests for Applications (RFA), recruit and train future employees, retrain or upskill current workers, expand education programs, relocate, hold town halls and listening sessions, and much more. Therefore, implementing just transition policies must involve strong community buy-in and dialogue with frontline and vulnerable communities at all stages of policy design, implementation, and evaluation, in order to detect and resolve issues in real-time.

State and local agencies will be primary players in driving change in the fuel, vehicle, and transportation services supply chains, as well as in directly or indirectly influencing transportation expenditures. As key investors in infrastructure, they can use their purchasing power to ensure quality employment practices. Through the state and local workforce development and education systems, they can ensure pipelines only go to high-quality jobs.

Using their power to audit and mandate accountability, they can ensure that frontline and vulnerable communities have a seat at the table and that employers are holding true to their promises of ensuring quality employment.

13 Future Research Needs

13.1Public charging infrastructure

What is the public sector role in expanding electricity charging infrastructure for both passenger and goods movements, including fast charging, grid integration and enhancement, and serving residents of multi-family buildings? And what are the strategies for advancing vehicle electrification among new mobility providers, including ride-hailing, microtransit, and carsharing.

13.2Ownership, use and safety of automated (autonomous) vehicles (AVs)

How will AVs be used, and what impact will that have on society? How can policies be formulated to ensure best outcomes? Analyze vehicle purchase and usage behavior of individuals, usage by new mobility companies, and conditions under which AVs are safe (enough).

13.3Freight efficiency and impacts

The potential benefits of improved freight efficiency to the economy and environment and the well-being of many communities is large. Cost-effective infrastructure investments and operational strategies can reduce costs and truck travel, while mitigating environmental and health impacts (particularly in disadvantaged communities) in California. The need for research is particularly compelling because freight plays a huge role in the economy, is a major source of urban air pollution and greenhouse gas emissions and a principal concern of environmental justice communities, and yet data availability is poor.

13.4Strategies to reduce passenger VMT

The effectiveness of policies implemented to reduce passenger VMT can be evaluated, including substituting telecommunications for travel, intensifying land use, increasing load factors in all passenger vehicles (including buses and ride-hailing), and greater use of micromobility and microtransit. Future VMT will be determined by a complex set of demographic, land use, behavioral, and transportation system factors. Key research questions include: persisting behavioral changes in post-COVID era, including use of e-commerce, telecommuting, tele-health, transit, ride-hailing, bicycling, and air travel; role of micromobility and active mobility; opportunities and implications for intensified land use; and effect of increased access to broadband and improved transit services in more rural areas of the state. How and under what circumstances will coupling of these strategies with other transportation, land use, or fiscal policies increase (or decrease) VMT.

13.5 Mobility and accessibility of physically and economically disadvantaged travelers

How can VMT be reduced for these travelers while increasing accessibility? What strategies would be most effective for underserved communities? What are the best strategies for mitigating any regressive impacts of transportation pricing policies to reduce VMT? Partnering with organizations with an equity focus, to evaluate metrics to assess and improve transportation access and improve environmental and health outcomes should be included in future research projects.

13.6 Vehicle purchase decisions are affected by many policies

How effective are different financial incentives (prices, taxes, fees, subsidies), what are the equity implications, and what new incentives could be adopted that accelerate the purchase of EVs while minimizing the burden on taxpayers? What is and will be the effect of increased availability of ridesharing, micromobility, and microtransit on vehicle ownership? What are the best ways to provide incentives for EVs to underserved communities? Research to conduct how to best serve all communities should assess used EV incentives, like the Clean Cars 4 All program and other “Cash for Clunkers” concepts.

13.7 Public finance of transportation

How should the shrinking role of gasoline and diesel taxes be addressed? How can and should transport infrastructure and services be supported by government? Should public funding be used to support public-private partnerships for infrastructure and mobility services? Should the state transition from fuel taxes to pay for roadway infrastructure to a VMT-based fee? If so, research is needed on ensuring an equitable structure, protecting privacy while ensuring revenue is apportioned appropriately.

13.8 Costs and Performance of New Propulsion Technologies

The transition to a carbon neutral transportation system will require the deployment of novel fuel, vehicle, and mobility technologies at a massive scale. Additional research on specific key technologies could help inform the decisions California must make in the years to come. Several priority research needs include understanding the various advanced alternative liquid fuel technologies that are approaching commercial-readiness to determine how each could contribute to a carbon-neutral fuel portfolio; improving end-of-life practices for ZEV components, especially batteries, and determining whether the optimal use for them is recycling, repurposing, or something else; and rate of improvement of electric and fuel cell vehicles, hydrogen, and advanced biofuels. What are the consequences if certain technologies progress either faster or slower? The possibility of other new technologies emerging that improve vehicles and fuels further, or reduce their costs further, should also be explored in an on-going fashion. How can we ensure these alternative fuels are not further contributing to disproportionate burdens on disadvantaged communities?

13.9Costs of Rapid Transitions

The transitions to ZEVs considered in this study are among the fastest transportation technology transitions (particularly for power trains) that has ever occurred Apart from consumer acceptance and demand, there are many uncertainties in undertaking such a rapid transition. Production of vehicles and vehicle components (and underlying resources such as platinum, lithium) will need to be ramped-up very quickly, under uncertainty and with tremendous levels of annual investment. Whether this rapid uptake of technologies triggers any financial or resource cost discontinuities is an important area for research. Other negative impacts include the lack of standardization of technologies like charger types, and potential stranded assets in older technologies that are not ultimately widely used. On the other hand, faster uptake of new vehicle technologies could reduce costs due to faster learning and scale effects. Market and cost effects of this rapid transition are worthy of a deeper analysis than could be undertaken in the current study.

13.10 Production, Distribution and Use of Alternative Fuels

Electricity will likely be the dominant energy for transportation in the future, but hydrogen and biofuels are likely to pay a role, as well as synthetic fuels made with electricity. A large range of studies are needed to analyze costs of production, distribution, and end use and performance of these new energy sources. Some specific issues include availability of waste or non-food oils, geological resources for sequestering carbon dioxide emissions safely and permanently, and landscapes for energy storage systems, such underground storage of hydrogen or renewable methane, and the capacity of California’s natural and working lands to sequester carbon given expected climate change. Further, the environmental externalities of particulate emissions from these fuels should be studied to determine impacts on public health, especially in disadvantaged communities.

13.11 Integration of Transportation and Electric Systems

Plug-in vehicles will be a significant source of new demand for electricity, for both passenger and freight vehicles. While bulk power demand is not expected to overwhelm supply, unplanned charging at certain times of day and locations, especially for fast charging, could stress distribution systems. Early research has also shown a strong promise for transportation to provide positive grid services, for example by coordinated charging when low-cost renewable energy is available on the grid, or potentially discharging to serve load in times of high demand or during outages. Similarly, hydrogen can be used to store excess electricity, again providing an opportunity to integrate transportation and electricity.

13.12 Transportation Systems Resilience

There is a significant gap in available research and tools for measuring and improving the resilience of transportation systems as they transition to zero emission. Transportation is essential for community resilience, for example by providing egress and mobility before, during, and after natural and climate disasters. Electric vehicles may provide a challenge to resiliency in that they rely on the grid to charge, they may also provide benefits by providing emergency power to key facilities. More research is needed to explore the potential for resiliency in a zero emissions transportation system.

13.13 Labor and Employment Implications of a transition to ZEVs?

Transitioning to 100% ZEV sales will have implications for labor and employment in the auto industry as well as supporting infrastructure, including changes in the type and amount of maintenance and repair of ZEVs. What are the labor implications and what training programs might be adopted to ease the transition? Similarly, what are the labor implications for a phasing out of gasoline and diesel fuels, and increased use of charging and hydrogen, including installing electrical infrastructure and charging stations? The first challenge is data to characterize and profile highly impacted workers in terms of occupation- and industry-specific demographic data.

13.14 Evaluation and Cost-Effectiveness

California and other governments have and continue to invest in a wide variety of incentive and other policies to support the transition to zero-carbon transportation. Embedding research and evaluation into programs, and completing credible, peer reviewed evaluations of programs would support future efforts to increase the effectiveness of the state’s investments.

14 Appendices

14.1 Light-duty Vehicle Appendix: TCO Calculation

Details of the assumptions and the source/literature used for deriving the components of the TCO model is given in Cost of Plug-in Electric Vehicle Ownership in California - A Total Cost ownership Analysis through 2030. Additional assumptions for the demonstration scenario illustrated here are given below.

14.1.1 (i) Capital Cost Calculations - Main Assumptions

- The cost of charging infrastructure varies for each market segment based on their ability to install a Level 2 charger at home. Ability to install a charger at home is calculated using eVMT survey data (2020 data)

Table 14.1. Probability of Charger Installation for Single-family Homes

Probability of installing Level 2 charger at home			
Home power option share of L2	less than $75k	$75-200k	greater than $200k
single-family	0.6	0.7	0.8

- Cost of charger installation is assumed to be $1,800 (NREL study: https://data.nrel.gov/submissions/130)
- Only households in single detached homes bear the cost of charger installation. Only one charger is installed per household (single detached home). Charger cost is divided by the number of PEVs in the household to account for the division in installation cost when subsequent PEVs are bought.

14.1.2 (ii) Capital Cost Calculations- Teardown Estimate of Vehicle Price

- For ZEV vehicles the capital cost is obtained using a teardown approach. The details of the teardown approach are found here: Cost of Plug-in Electric Vehicle Ownership in California - A Total Cost of Ownership Analysis Through 2030
- Vehicle purchase price changes corresponding to changes in components of the vehicle technology tightening of CAFE standards for gasoline vehicles, manufacturer profit margin, dealer markup, and research and development expenditure per vehicle.

Table 14.2. Purchase cost of Plug-in Electric Vehicles (Teardown Approach)

	BEV_PC_Short	BEV_PC_Mid	BEV_PC_Long	BEV_PT_Short	BEV_PT_Mid	BEV_PT_Long	PHEV_PC_Short	PHEV_PC_Long	PHEV_PT_Short	PHEV_PT_Long
Total 2020	$32,934	$36,037	$40,388	$43,231	$48,294	$56,314	$32,013	$37,336	$40,150	$48,228
Total 2025	$30,104	$32,791	$36,755	$39,492	$43,873	$51,297	$30,944	$35,488	$39,163	$42,116
Total 2030	$27,202	$29,622	$33,367	$36,323	$40,265	$47,378	$28,919	$33,240	$37,310	$43,743

- For gasoline vehicles, consider the average MSRP (fueleconomy.gov) of top five vehicle models (by sale numbers in 2019) in the midsize and near luxury segment of PC and PT categories. The CAFE standards are assumed to get tighter between 2020 and 2030 and compliance leads to higher capital cost for gasoline vehicles.

Table 14.3. Purchase cost of ICEVs

ICEV_PC_NL	ICEV_PT_NL	ICEV_PC_LU	ICEV_PT_LU
$24,687	$35,405	$43,813	$59,790
$25,180	$36,113	$44,689	$60,985
$25,674	$36,821	$45,565	$62,181

14.1.3 (iii) Operating Cost Calculations- Assumptions

- For BEVs and PHEVs, annual VMT is split into home, workplace, and public charging with home priority until 2025 and work priority charging from 2025–2045.
- The split between home, work, and public charging differs by the income, housing category, and the probability of commuting for the particular housing type and income category. Also, by the number of PEVs in the household.
- The assumptions for fuel cost and vehicle efficiency are given in Table 14.4 and Table 14.5.
- Utility factor for PHEV-40 is assumed to be 0.7 and for PHEV-80 it is 0.85.

Table 14.4. Fuel price assumptions

Fuel Price ($)	2020-2025	2026-2030	2031-2045
Gas price ($/gallon)	3.68	4.08	4.35
Electricity home ($/kWh)	0.17	0.17	0.17
Electricity work ($/kWh)	0.2	0.12	0.12
Electricity public ($/kWh)	0.22	0.22	0.22
Hydrogen ($/kg)	12	8.5	7

Table 14.5. Vehicle Efficiency assumptions

Fuel Efficiency	2020–2025	2025–2030	2030–2045
BEV PC SR (kWh/mile)	0.28	0.23	0.23
BEV PC MR (kWh/mile)	0.29	0.26	0.26
BEV PC LR (kWh/mile)	0.3	0.28	0.28
BEV PT SR (kWh/mile)	0.36	0.32	0.32
BEV PT MR (kWh/mile)	0.4	0.36	0.36
BEV PT LR (kWh/mile)	0.43	0.4	0.4
PHEV-40 PC (kWh/mile)	0.35	0.35	0.35
PHEV-80 PC (kWh/mile)	0.43	0.43	0.43
PHEV-40 PT (kWh/mile)	0.33	0.33	0.33
PHEV-80 PT (kWh/mile)	0.6	0.6	0.6
Gas PC (mpg)	26	32	32
Gas PT (mpg)	22	27	27
FCEV PC (Mile/kg)	67.6	71.3	75.4
FCEV PT	47.1	48.7	50.3
PHEV Gas efficiency (MPG)	32	32	32

14.1.4 (iii)Total Cost of Ownership and Cost of Adoption Calculations - Model

The method used to calculate the cost of adoption for the six household categories and the proportion of households is each category benefiting from fleet transition: we use the new vehicle sales estimates for each type of household in California defined based on their income, dwelling type, number of household vehicles, and number of PEVs to calculate the weighted average cost of adoption. The new sales estimates were calculated in Tool 1 of the three-step scenario model presented here.

Table 14.6. Total cost of ownership calculation

	Model
Capital cost	$Capital\ cost = \frac{Vehicle\ purchase\ price * APR}{(1-(1+APR)^{-N})} + \left(RC + \rho * \left(\frac{CI\_L2_{home}}{Number\ of\ PEVs}\right)\right) CRF$ · *RC*= registration cost · *APR*=0.05 and *CRF*=0.08 · CI_L2home= Cost of charger installation at home ($1800) APR: interest rate for loans for an average credit score CRF: capital recovery factor
Operating cost	$Operating\ cost = \sum_{t=1}^{n} \frac{(Fuel\ Cost + ARC + IC + MT_t)}{(1+i)^t}$ · ARC= annual registration cost · IC= annual insurance cost · MT= annual maintenance cost · i=real interest rate (=1.25% which is the current interest rate of US treasury bonds with a residual maturity of five years · t= lifetime of the vehicle
Resale value	5% of vehicle purchase price
Annualized TCO	Capital cost + Operating cost + Resale value

14.2VMT Appendix: VMT Topic Policy Scenario Descriptions

For the LC1 scenario that identifies a target of a 15% reduction in per-capita VMT relative to the BAU case, several strategies would be combined to achieve this goal. The potential for doing that and how each strategy would contribute, based on the detailed analysis conducted in the project, is described in the appendix to the main project report.

14.2.1 Built Environment Strategies

The effect of built environment elements of this VMT analysis are captured primarily through the spreadsheet analysis model by census tract described above. This spreadsheet analysis model uses a set of rules to define place types and to associate VMT levels specific to those place types and how they are expected to evolve over time.

The built environment, comprising land use patterns and transportation infrastructure, has an important influence on vehicle travel [372]. What activities are located where and how they are linked together determine the choices available to individuals and shape the choices they make about destinations, travel modes, and frequency of trips, which together determine their vehicle-miles of travel (VMT). The empirical literature on these relationships provides strong evidence of associations between various elements of the built environment and travel behavior (Table 14.7). Although the degree to which these associations represent a causal effect of the built environment on travel behavior is uncertain, many studies have found strong effects even after accounting for the tendency of households to live in places that are consistent with their preferences for different travel modes, a phenomenon known as “residential self-selection” [112], [373].

Table 14.7. Estimated Effects on VMT of Built Environment Elements Based on Empirical Literature

Element	Effect Size
1. Residential density	0.05% to 0.12% reduction in VMT per 1% increase in density
2. Employment density	0.03% reduction to 0.07% increase in VMT per 1% increase in density
3. Land-use mix	0.01% to 0.17% reduction in VMT per 1% increase in mix
4. Regional accessibility	0.13% to 0.25% reduction in VMT per 1% increase in accessibility
5. Network connectivity	0.12% reduction in VMT per 1% increase on connectivity, but variable
6. Public transit service	0.5% increase in transit ridership per 1% increase in service frequency
7. Bicycle facilities	0.32% to 0.36% increase in bicycle commuting per 1% increase in miles of bike lanes; up to 0.01% in car commuting reduction per 1% increase
8. Pedestrian facilities	0.09% to 0.27% increase in walking per 1% increase in sidewalk length

Source: SB375 Research, available: https://ww2.arb.ca.gov/our-work/programs/sustainable-communities-program/research-effects-transportation-and-land-use

For the purposes of this analysis, the built environment consists of all elements listed in Table 14.7, as well as other associated characteristics. Increases in all of these elements would result in lower VMT, according to the available empirical evidence. Higher levels of the first four elements are characteristic of compact development (in contrast to sprawling development). These eight elements are strongly correlated with each other, and changes in any one element often accompany changes in other elements. Higher levels of elements 5 to 8 enhance the viability of alternatives to driving (in contrast to auto dependence). The two support each other: more compact development makes alternatives to driving more viable, while alternatives to driving make compact development more viable. These interconnections justify the place-based approach to estimating the effects of built environment characteristics on VMT that is described below.

Changes to the built environment may make it possible to drive less, but these measures will reach their full potential only if people have viable alternatives to driving. To make these alternatives attractive, it is typically necessary to discourage driving by increasing its generalized cost, i.e., by implementing pricing policies that target vehicle miles traveled and parking in core urban centers. Similarly, pricing policies will have more impact if combined with changes to the built environment that enhance viable alternatives to driving. For simplicity, the modeling of VMT reduction strategies in this project provides estimates of the effect of each type of strategy without assuming the adoption of the other. The overall estimate assumes that the effects are additive, but it is quite possible that the impact of some measures will increase substantially in the presence of several others, and conversely that the collective impact of some measures will be less than the sum of its parts. It is also important to recognize that highway expansion makes driving easier (and cheaper) and works against the goal of reducing VMT. Research shows that a 1% increase in highway capacity leads, over a period of five to ten years, to a 1% increase in VMT [39].

The analysis of the VMT reduction potential of built environment strategies relies on broad-brush assumptions about the effects of such strategies on place types. Although the model considers changes to the built environment at the census tracts level, this approach does not does not take into account development potential in specific places or provide a forecast of where development is likely to occur.

Our analysis uses Salon’s classification of census tracts by place type [374] (Table 14.8), and makes the core assumption that place types capture all relevant elements of the built environment that affect VMT, including land use and transportation characteristics such as those listed in Table 14.7. The variables used by Salon to define place types include population density, job accessibility, restaurants within walking or driving distance, road density, percent commuting by transit, median value of housing units, percent of units single-family, percent of units less than 10 years old, and percent of units more than 60 years old). Salon’s assignment of place type to each census tract in California, using the tract system for the 2000 Census, is the starting point for our analysis.

The effects of built environment policies are represented in the model by adjustments to population growth rates by place type. These adjustments result in some shifting of census tracts to new place types, with higher or lower VMT per capita, depending on changes in density resulting from population growth or decline. The approach involves two key assumptions:

1. Adjustments to population growth rates by place type to reflect built environment strategies.
2. Density thresholds at which census tracts shift to a different place type.

14.2.1.1 Adjustments to growth rates by place types

The model uses population 5-year growth rates by census tract compatible with county-level projections from the California Department of Finance as a baseline. Additive adjustments to these growth rates are made by place type, as a way to represent the effect of built environment strategies; the adjustment is the same for all tracts of a particular place type, regardless of their growth rates.

To maximize reduction in VMT in this framework, two general approaches are possible: 1) put more people in places with low VMT per capita to start with, or 2) put enough people in higher VMT places that they become lower VMT places. Using Salon's place types, the former is done by increasing population growth rates in the place types "central city urban" (e.g., downtown San Francisco, downtown Los Angeles) and "urban high public transit use" (e.g., downtown San Jose, downtown Sacramento). The latter is done by increasing population growth rates to the point that the new population densities are high enough to shift tracts from single-family, suburban, and low public transit use place types to multifamily, urban, and high public transit use types. The assumed adjustments to population growth rates by place type for the policy scenario, as shown in Table 14.8 reflect a combination of these two approaches.

The adjustments are based on the average 5-year population growth rates for each place type at the baseline, under the rationale that these growth rates are a good general indicator of the degree of change that is possible in each place type (though some tracts within a given type will change far more than others). The adjustment for "central city urban" represents a doubling of population growth in these areas through high-density housing development. The adjustments for suburbs with multi-family and urban high transit use are double the current average growth rate for that place type. The adjustment for "urban low transit use", which has had a negative after growth rate, is twice the average growth rate but positive. The adjustments for "suburb with single-family" and "rural" are negative, so as to reduce the number of people living in places that have relatively high average household VMT. In theory, high population growth in these tracts could increase densities enough that they would shift to lower VMT place types, but for this analysis the assumption is that such changes are infeasible and/or not desirable. Tracts classified as rural in urban include areas unlikely to develop, such as military facilities, but also special development opportunities, such as the Railyards in Sacramento. Given the special nature of these tracts, no adjustment is made to their tract-level growth rates. Tracts in the preserved place type have had declining population on average and are not appropriate for development; no adjustment is made to the growth rate for these tracts. Policy assumptions underlying these adjustments are summarized in Table 14.8.

Table 14.8. Policy Assumptions and Population Growth Rate Adjustments by Place Type

Place Type	Avg HH VMT	Policy Assumption	Average 5-year growth rate	Adjust-ment
1 Urban low public transit use	41.70	Densification encouraged through up-zoning, plus improvements in transit service	-1.34%	+2.7
2 Suburb with MF	40.99	Improvements in public transit service, with some encouragement of further densification	1.45%	+2.9
3 Central city urban	17.45	Housing development encouraged through zoning changes and tax incentives.	3.82%	+3.8
4 Rural	50.27	Development outside of metropolitan areas discouraged	0.66%	-1.4
5 Suburb with SF	59.66	Development generally discouraged	0.22%	-0.5
6 Urban high public transit use	36.80	Housing development encouraged through zoning changes and tax incentives, with public transit improvements as needed	0.39%	+0.8
7 Rural in urban	41.09	No adjustment to growth rates, though some locations have substantial growth potential	0.40%	0
8 Preserved	n/a	No adjustment to growth rates	-0.54%	0

14.2.1.2 Density Thresholds for Reassigning Place Types

The adjustments are added to the 5-year population growth rates for each census tract and population densities are recalculated for each 5-year period. The new population densities are used to reassign place types for each census tract based on the thresholds listed in Table 14.9 (if the density increased) and Table 14.10 (if the density decreased). This approach assumes that the other built environment elements that define place types change in conjunction with the change in population density and that the effect on VMT of all strategies affecting the built environment will be accounted for by changes in place type.

The density thresholds by which new place types are assigned are based on average standardized population densities, as reported by Salon (2014) [374]. To be assigned to a new place type, the new population density for a census tract, standardized relative to the state average*, must equal or exceed the specified threshold (or equal or fall below the specific threshold if population is declining). We also assumed that a census tract may shift only one step (e.g., from urban low transit use to urban high transit use but not to central city urban) in one five-year time period. The rules by which census tracts are reassigned are specified in Table 14.9 for tracts with increasing population densities and Table 14.10 for tracts with decreasing population densities. VMT for each tract is calculated based on population density, average VMT per household for that place type, and population per household for that place type.

Table 14.9. Density thresholds for place types if density is increasing

A Current Place Type	B New Std Pop Density	C New Place Type
1 Urban low public transit	> 1.6	6 Urban high transit
2 Suburb with MF	> 1.6	6 Urban high transit
3 Central city urban		3 Central city urban
4 Rural	> -0.6	5 Suburb with SF
5 Suburb with SF	> 0.08	2 Suburb with MF
6 Urban high public transit	> 2.9	3 Central city urban
7 Rural in urban	> 1.6	6 Urban high transit
8 Preserved		8 Preserved

Table 14.10. Density thresholds for place types if density is decreasing

A Current Place Type	B New Std Pop Density	C New Place Type
1 Urban low public transit	< 0.08	2 Suburb with MF
2 Suburb with MF	< -0.6	5 Suburb with SF
3 Central city urban	< 1.6	6 Urban high transit
4 Rural		4 Rural
5 Suburb with SF	< -0.8	4 Rural
6 Urban high public transit	< 0.08	2 Suburb with MF
7 Rural in urban	< -0.8	4 Rural
8 Preserved		8 Preserved

* Standardized population density = (population density – state mean population density)/(standard deviation of population density)

14.2.2 Pricing Strategies

Transportation pricing strategies include adjusting fuel taxes, perhaps transitioning to VMT-based road-usage fees, parking pricing, dense area cordon pricing, and other localized measures such as adjusting bridge tolls and installing corridor-level HOT lanes. The major strategies addressed in this study are discussed in additional detail below.

14.2.3 Fuel Tax and Mid-century Road-Usage Fee

This policy combines a fuel (i.e., gasoline and diesel) tax starting in 2030 with a distanced-based road-usage fee in 2040. The next two subsections provide the methodological approach employed to determine the per capita VMT change of these two complementary policies. We note that all monetary values are in 2020 US dollars; therefore, the implementation of a proposed fuel tax increase or distanced-based road-user fee in a later year must be adjusted based on the (expected) inflation rate.

Unlike other VMT policies laid out in this report, these two pricing policies are quite specific in terms of how an increase in the gas tax or distance-based road-user fee would affect VMT. This specificity should not be confused with certainty, as it pertains to the elasticity parameters. There is considerable uncertainty associated with the elasticity of VMT with respect to pricing changes. Nevertheless, the values in this section should provide a good estimate of the order of magnitude of pricing needed to reduce VMT per capita by around 5%.

It is also important to note that while the modeling framework assumes the policies in this report are additive in terms of their impact on VMT, making it more expensive to drive (i.e., consume vehicle miles) is critical to unlocking the benefits of the other policies.

14.2.3.1 Fuel Tax

Given the state of California recently increased the state's gasoline tax by \$0.12 per gallon and the diesel tax by \$0.20 per gallon (*SB-1 Transportation Funding*, 2018), we assume that an additional increase in the fuel tax is infeasible in 2025. Rather, an increase in the gasoline/diesel tax is proposed for 2030.

Let

c^f	denote the size of the fuel tax increase in \$/gal
$c^{f,0}$	denote the current cost of fuel in units of \$/gal.
σ^f	the percent change in the cost of fuel associated with a fuel tax

$$\sigma^f = c^f / c^{f,0}$$

The Salon (2014) report includes values for the elasticity of VMT with respect to the cost of fuel. Let ε_p^f denote this elasticity for each place type. The second row of Table 14.11 displays the values of ε_p^f for the seven place types, estimated empirically with a Tobit model in Salon (2014). The third row displays the values of ε_p^f used in our study. We rounded the Salon (2014) significant digits to two significant digits in order to avoid false precision. Moreover, we assume that there is a small, rather than zero, impact of fuel prices on VMT in central city, rural, and rural- in-urban areas.

Table 14.11. Elasticity Values from Fuel Tax Policy/Strategy

	Urban Low Public Transit	Suburb MFH	Central City	Rural	Suburb SFH	Urban High Public Transit	Rural in Urban
Salon (2014) Elasticity Values	-0.113	-0.102	0	0	-0.0969	-0.203	0
Our Elasticity Values	-0.11	-0.10	-0.03	-0.03	-0.10	-0.20	-0.04

There is one other piece of relevant data to calculate the percentage change in household VMT per capita in year t in place type p, denoted by ${\pi^f}_{t,p}$ with respect to the percent change in the cost of fuel, namely the proportion of the population to which the elasticities in Table 14.11 apply. Necessarily, the elasticities apply to the proportion of household VMT wherein the vehicle is gasoline fueled. Table 14.12 below displays the scenario and light-duty vehicle teams estimates for the CA fleet proportion of gasoline-fueled vehicles in five-year increments. Let ${\theta_t}^f$ denote the proportion of gasoline-fueled vehicles in the California fleet in year t.

Table 14.12. Assumed Gasoline Vehicle Market Shares Over Time

Year	Assumed Gasoline-fueled Vehicle Market Share
2025	90.6%
2030	77.1%
2035	55.3%
2040	33.8%
2045	18.8%

Hence, to calculate ${\pi^f}_{t,p}$, our parameter of interest, we need to multiply our percent change in the cost of fuel σ^f (due to the fuel tax c^f) by the elasticity of household VMT in place type p, ${\varepsilon_p}^f$ and by the proportion of gasoline-fueled vehicles in year t, ${\theta_t}^f$. This relationship is shown in the equation below:

$${\pi^f}_{t,p} = \sigma^f \times {\varepsilon_p}^f \times {\theta_t}^f$$

The values for all of the input parameters, policy variables, and auxiliary variables related to the above equation are shown in Table 14.13.

Table 14.13. Analysis Variables for Fuel Tax Policy Analysis

Input Parameter	Value
$c^{f,0}$	\$3.50/gal.
ε_p^f	See Table 14.11
$\theta_t{}^f$	See Table 14.12
Policy (i.e., Decision) Variable	
c^f	\$0.40/gal.
Auxiliary Variables	
$\sigma^f = c^f / c^{f,0}$	11.4%

14.2.3.2 Mid-Century Distanced-Based Road-Usage Fee

As the impact of a fuel tax will degrade over time due to the expected decline in the proportion of gas-fueled vehicles on the road ($\theta_t{}^f$), we consider a supplemental policy, referred to as the distanced-based road-usage fee. We assume that rather than replacing the gasoline tax, the distanced-based road-usage is complementary in order to continue disincentivizing gasoline-fueled vehicles.

Similar to the methodology for obtaining the percentage change in household VMT per capita for a fuel tax increase, to calculate the percentage change in household VMT per capita in year t, in place type p for a distance-based road-usage fee,$\pi^f{}_{t,p}$, we need:

- a VMT elasticity for each place type for the distanced-based road-usage fee, ε_p^r
- the percentage change in cost to drive a mile on the road, σ^r, which is a function of
- the proposed distanced-based road-usage fee, c^r
- the current distanced-based cost to drive on the road, $c^{r,0}$

However, unlike with the fuel tax, the distanced-based road-usage fee would apply to all household vehicles, not just the gasoline-fueled ones.

Unfortunately, because a road-usage fee has not been implemented at scale in the U.S., robust estimates of the elasticity parameter are not available in the academic literature. Salon et al. (2012) [372] reviewed the literature related to road pricing and found one analysis of a pilot distance-based road-user charging program in Oregon along with several other studies that use transportation system simulation models to estimate the impact of distance-based road-usage fees on VMT. Unfortunately, the Oregon distanced-based road-usage fee replaced the fuel tax rather than complementing the fuel tax. One of the simulation-based studies (funded by CARB), while older, does focus on metropolitan regions in California and finds elasticity values around -0.20 to -0.25 (Deakin et al., 1996) [375].

Given these values from Deakin et al. (1996) and our assumption that a distance-based road-usage fee will be more impactful on VMT than a fuel tax[26], we use the following values for distanced-based road-usage fee elasticity, ε_p^r, as shown in Table 14.14 below.

Table 14.14. Elasticity Estimates for Road Usage Fees

	Urban Low Transit	Suburb MFH	Central City	Rural	Suburb SFH	Urban High Transit	Rural in Urban
Our Elasticity	-0.2	-0.2	-0.05	-0.05	-0.2	-0.3	-0.05

To calculate ${\pi^r}_{t,p}$, our parameter of interest, we need to multiply our percent change in the cost of driving on the road, σ^r(due to the fuel tax, c^r) by the elasticity of household VMT in place type p, ε_p^r. This relationship can be written:

$$ {\pi^r}_{t,p} = \sigma^r \times \varepsilon_p^r $$

The values for all of the input parameters, policy variables, and auxiliary variables related to the above equation are shown in Table 14.15. According to the American Automobile Association (AAA), the average all-in cost to drive one mile in a motor vehicle is $0.55/mi in 2020. We assume an aggressive distanced-based road user fee of $0.15/mi. resulting in an increase in driving cost per mile of 27%.

Table 14.15. Elasticity Estimates for Road Usage Fees

Input Parameter	Value
$c^{r,0}$	$0.55/mile
ε_p^r	See Table W
Policy (i.e., Decision) Variable	
c^r	$0.15/mile
Auxiliary Variables	
$\sigma^r = c^r / c^{r,0}$	27%

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[26] A distanced-based road-usage fee is a direct tax on vehicle mileage (i.e., distance); whereas, a fuel tax is a direct tax on fuel consumption and an indirect tax on vehicle mileage.

14.2.3.3 TNC Pooling Incentives

The evidence in the literature related to ride-pooling (also known as ride-splitting) on VMT is mixed. From one perspective, a ride-pooling trip definitely reduces VMT compared to a similar ride-hailing trip. However, it appears that ride-pooling, when service providers incentivize it through low prices, tends to draw travelers away from public transit and possibly active transport modes.

Du and Rakha (2020) [376] state that there are few comprehensive conclusions to draw between VMT and ride-[hailing] based on the literature. Shaheen and Cohen (2019) [297] find that while there are only a few published studies related to shared-ride (and ride-pooling) services, empirical and anecdotal evidence does suggest that pooling provides various environmental benefits (e.g., energy consumption and emissions, congestion mitigation, etc.).

Using a powerful but simple model, Santi et al., (2014) [377] provide an upper bound on the benefits of ride-pooling—a 40% reduction in VMT over existing taxi services in New York City. Hyland and Mahmassani (2020) [378], in their simulation study that employs optimization techniques to dynamically route vehicles and match vehicles to traveler requests, show about a 20% decrease in VMT through ride-pooling compared to a ride-hailing service. This large decrease in VMT comes even in the case where the vehicles can serve at most two requests and the maximum user in-vehicle detour times are quite small.

Unfortunately, the literature does not provide any forecasts for the share of trips (or miles) served by TNCs (ride-hailing and pooling) in the future. As such, we assume the following market share for TNCs in each place type in five-year increments.

Table 14.16. TNC Market Shares by Place Type and Year

Year/PT	Urban Low Public Transit	Suburb MFH	Central City	Rural	Suburb SFH	Urban High Public Transit	Rural in Urban
2025	10%	5%	5%	1%	5%	5%	1%
2030	15%	8%	10%	2%	8%	8%	2%
2035	20%	12%	15%	3%	11%	11%	3%
2040	25%	17%	20%	5%	15%	15%	5%
2045	30%	25%	25%	7%	20%	20%	7%

Henao and Marshall (2019) in Denver and Schaller (2018) in New York City find that 13% and 37% of requests were for pooled-ride services but only 2% (in a relatively small sample size) and 22% of trips involved sharing-a-ride with a stranger, respectively. Given the limited data on this parameter and the variance between Denver and New York City, we assume the following values for the business-as-usual pooling ratio (i.e., the ratio of pooled TNC trips over the total number of TNC trips).

Table 14.17. TNC Pooling Ratios by Place Type

Urban Low Public Transit	Suburb MFH	Central City	Rural	Suburb SFH	Urban High Public Transit	Rural in Urban
30%	20%	35%	5%	10%	30%	5%

Our policy/strategy is to increase these pooling ratios considerably via incentivizing (i) TNCs to offer and promote pooling services, and (ii) users to choose pooling services when making a TNC trip. Given heavy incentivization, we believe the following pooling ratios are achievable.

Table 14.18. Resulting TNC Pooling Ratios with Policy Change

Urban Low Public Transit	Suburb MFH	Central City	Rural	Suburb SFH	Urban High Public Transit	Rural in Urban
65%	50%	60%	10%	40%	65%	10%

Using the 20% value for the decrease in fleet VMT in pooled-ride services compared to ride-hail services in Hyland and Mahmassani (2020) [378], we find the following percent decrease in VMT (per capita) from incentivizing pooling.

Table 14.19. Percentage Decreases in VMT From Pooled Ride Services by Place Type

Year/PT	Urban Low Public Transit	Suburb MFH	Central City	Rural	Suburb SFH	Urban High Public Transit	Rural in Urban
2025	0.70%	0.30%	0.25%	0.01%	0.30%	0.35%	0.01%
2030	1.05%	0.48%	0.50%	0.02%	0.48%	0.56%	0.02%
2035	1.40%	0.72%	0.75%	0.03%	0.66%	0.77%	0.03%
2040	1.75%	1.02%	1.00%	0.05%	0.90%	1.05%	0.05%
2045	2.10%	1.50%	1.25%	0.07%	1.20%	1.40%	0.07%

The value 0.75% comes from 15% market share x (55% - 30%) pooling ratio x 20% decrease in VMT from pooling.

14.2.3.4 Cordon Pricing in Dense Urban Areas

As discussed above, several areas have instituted cordon pricing around dense cities, most famously in London, England that has had a priced cordon zone since 2003. Stockholm, Sweden has also had a program since 2007. These programs have had an enduring effect of reducing VMT and congestion, and are considered general successes.

The details of how much a cordon pricing scheme will actually reduce VMT and congestion in a given area is of course a complex function of many factors related to urban form, the level of pricing, the extent to which pricing is adjusted based on vehicle type (e.g., gross vehicle weight, engine size, and vehicle age, which correlate with its vehicle energy use per mile traveled and its emissions of air pollutants), the extent to which waivers of the fees are given to low income people to help correct for the fundamentally regressive nature of this type of pricing policy, and so on. Given the lack of experience with such programs in the U.S. there is thus considerable uncertainty about the actual impacts of these policies, but certainly the European experience is encouraging that they can be successful.

For purposes of this study, we assume that around 2030 there is a cordon pricing policy enacted for four major urban areas in California: Los Angeles, San Jose, San Francisco, and San Diego. We further assume the magnitude of the fee and nature of it is similar to London, where the fee is approximately 15 pounds ($18) per vehicle at present, having risen some every 3-4 years from an initial level of 5 pounds ($6) in 2003. Residents within the city could receive a 90% discount, and registered disabled people could be exempt from the fee. We further assume that the fees and any discounts given to clean-fuel vehicles, especially ZEVs, are calibrated over time to maintain the initial reductions in VMT from the pricing policy.

Using the place types discussed above, and the general impacts of these policies seen in the literature (summarized in U.S. DOT, 2008 and discussed above) we assume that this strategy could produce about a 5% per capita VMT reduction impact in the urban low transit regions where it is applicable, about 3.75% in urban high transit areas near the cordon zones, about 1.25% in suburban single-family and multi-family areas, and negligible impacts in rural areas and the central cities themselves.

These estimates are then weighted by the importance of the place types as in other aspects of the analysis. As reported above in Table 14.19, we then find about a 1.8% statewide per-capita potential reduction from this “large urban area cordon pricing” strategy.

14.2.3.5 Parking Pricing

Parking pricing is a means of reducing VMT in urban areas by increasing the generalized cost of driving a personal automobile, thus encouraging other modes such as transit, active transportation, or micromobility, for example. Studies have examined both employee parking and more general parking pricing policies.

Employee Parking

Dueker et al. (1998) [379] focused on parking strategies as a means of reducing single-occupancy vehicle travel for work trips. By interviewing commuters from the 1990 Nationwide Personal Transportation Survey (NPTS) as a supplementary input of the NPTS data, the researchers simulated regionwide trips resulting from parking strategy implementations. Five West Coast metropolitan areas (Los Angeles, Sacramento, San Diego, San Francisco, and Seattle) were analyzed in this study.

As a result of a $3 increase for all employee parking spaces, a reduction of 1.6 percent of vehicle miles traveled (VMT) was found by averaging across all five metropolitan areas. In other words, the VMT elasticity regionwide is -0.53 percent per $1 daily parking surcharge.

14.2.3.6 Logic Behind Policy Extrapolation from 2025 to 2045

To produce the VMT elasticities, we applied the following factors, based on the cited literature and stated assumptions, as noted in Table 14.20 below.

Table 14.20. Factors Needed for Employee Parking Elasticities

Factors	Explanation	Source	Value
$DailySurcharge_{literature}$	The parking surcharge in dollars per day	Dueker et al. (1998)	$3
$DailySurcharge_{Assumption}$	The parking surcharge in dollars per day	Assumption	$1
$\%\,VMT\ Reduction$	Percentage of VMT reduced by increasing daily parking cost by $DailySurcharge_{literature}$	Dueker et al. (1998)	-1.60%
$Elasticity_{employee}$	Percentage of VMT reduced among employees by increasing daily parking cost by one dollar	Extrapolation	-1.19%
$\%\,Employed$	Percentage of population that are employed	American Community Survey (ACS) 2018 5-Year Estimates (U.S. Census Bureau [USCB], 2018)	44.70%

To have a more accurate estimate for each place type, their corresponding percentages of employed population were extrapolated from the ACS data collected in 2018 by taking the ratio of the total employed population over the total population (see Table 14.21).

Table 14.21. Percentage of Employed Population in Each Place Type (USCB, 2018)

Place Type	Employed Population	Population	$\%\,Employed$
Urban Low Transit	6,497,260	13,609,485	48%
Suburb with MF	5,632,038	12,833,200	44%
Central City Urban	313,988	509,778	62%
Rural	2,177,520	5,650,070	39%
Suburb with SF	6,963,155	15,620,918	45%
Urban High Transit	1,936,698	4,072,964	48%
Rural in Urban	1,038,957	2,627,353	40%
Preserved	157,257	353,081	45%

The elasticity and the corresponding VMT reduction estimate can then be derived using the formulas below:

$$Elasticity_{employee} = \frac{\%\,VMT\ Reduction}{DailySurcharge_{Literature} \cdot (\%\,Employed)} = -1.19\%$$

For a specific place type i:

$$Elasticity_i = Elasticity_{employee} \cdot (\%\,Employed_i)$$

$$Estimated\ VMT\ Reduction\ in\ place\ type\ i = (Elasticity_i) \cdot (DailySurcharge_{Assumption})$$

After the estimated VMT reductions were computed, we further assumed that suburbs and rural areas would experience no change due to the limited charged parking facilities there. Table 14.22 shows the adjusted VMT reduction over the baseline model for each place type.

Table 14.22. VMT Reduction V.S. Baseline (Employee Parking)

Place Type	$\%\ Employed$	$Elasticity_{employee}$	VMT Reduction (%)
Urban low transit	48%	-1.19%	-0.57%
Suburb with MF	44%		0.00%
Central city urban	62%		-0.73%
Rural	39%		0.00%
Suburb with SF	45%		0.00%
Urban high transit	48%		-0.57%
Rural in urban	40%		0.00%
Preserved	45%		0.00%

This effect, when translated into the net VMT reduction per 5 years, will reach the following values in each time frame, as shown in Table 14.23.

Table 14.23. Per-Capita VMT Reductions Over Time (5-Year Changes) by Employee Parking Pricing

	2025	2030	2035	2040	2045
VMT Reduction per capita	0.14%	0.00%	0.00%	0.00%	0.00%

With the VMT variation due to natural population movement netted out, the policy has little or no continuing effect in time frames after 2025.

All Parking

Frank et al. (2011) [380] analyzed the potential effectiveness of various policy strategies (e.g., urban form, parking costs) on the reduction of VMT and carbon emissions. With a combination of the travel data from 2006 Puget Sound Regional Council (PSRC) Household Activity Survey and the parking cost per Traffic Analysis Zone (TAZ), the study used linear regressions to build statistical models that estimated the VMT reduction with regard to parking cost increases. The study was conducted in the King County area of Washington State.

Results showed that a 3.21 percent decrease in VMT could be achieved by applying a parking cost of $0.28 per hour, whereas the reduction was 11.5 percent if the parking cost increased from $0.28 per hour to $1.19 per hour. Therefore, the VMT elasticity is -1.2 percent (assuming a 10-hour duration per day) to -2.4 percent (assuming five hours) per $1 daily parking surcharge. This was originally -11.5% for surcharge $0.28/hour to $1.19/hour. For the CalEPA VMT study, we assumed 10 hours of daily parking: -1.26% VMT per $1 surcharge [380].

Logic Behind Policy Extrapolation from 2025 to 2045

To produce the VMT elasticities, we applied the following factors, based on the cited literature and stated assumptions, as noted in Table 14.24 below.

Table 14.24. Factors Needed for All Parking Elasticities

Factors	Explanation	Source	Value
DailyParkTime	The total hours of parking per day	Assumption	10 hours
DailySurcharge	The parking surcharge in dollars per day	Assumption	$1
Elasticity	Percentage of VMT reduction per dollar per day	Extrapolation	-1.26%
HourlyCostold	The original parking cost in dollars per hour	Frank et al. (2011)	$0.28 per hour
HourlyCostnew	The increased parking cost in dollars per hour	Frank et al. (2011)	$1.19 per hour
% VMT Reduction	Percentage of VMT reduced by increasing hourly cost from HourlyCostold to HourlyCostnew	Frank et al. (2011)	-11.5% from $0.28 per hour to $1.19 per hour

The elasticity and the corresponding VMT reduction estimate can then be derived using the formulas below:

$$Elasticity = \frac{\%\,VMT\ Reduction}{(HourlyCost_{new} - HourlyCost_{old}) \cdot (DailyParkTime)} = -1.26\%$$

$$Estimated\ VMT\ Reduction = (Elasticity) \cdot (DailySurcharge) = (-1.26\%) \cdot (\$1) = -1.26\%$$

Similarly, suburbs and rural areas were assumed to bear no change in response to the parking price increase. Table 14.25 shows the adjusted VMT reduction over the baseline model for each place type.

Table 14.25. VMT Reduction V.S. Baseline (All Parking)

Place Type	Elasticity	VMT Reduction (%)
Urban low transit	-1.15%	-1.15%
Suburb with MF		0.00%
Central city urban		-1.15%
Rural		0.00%
Suburb with SF		0.00%
Urban high transit		-1.15%
Rural in urban		0.00%
Preserved		0.00%

The corresponding net VMT reduction per 5 years for each time frame is noted in Table 14.26.

Table 14.26. Per-Capita VMT Reductions Over Time (5-Year Changes) by Parking Pricing Applied to General Population

	2025	2030	2035	2040	2045
VMT Reduction per capita	0.30%	0.01%	0.01%	0.01%	0.01%

14.2.3.7 Transportation Demand Management (TDM) – Carpooling and Telework

Commute Trip Reduction (CTR) Program

To estimate the effects of the CTR program in Washington State, Hillsman et al. (2001) [381] analyzed the survey data in the Seattle metropolitan area and simulated the VMT reduction from the CTR program in 1999 using a four-step model, called EMME. Results indicated a 1.33 percent VMT decrease in all roadways during morning peak hours. It was concluded that trip reduction programs could reduce approximately 1 percent VMT regionally [382].

Carpooling

Herzog et al. (2006) conducted a survey (N=6,708) in 2004 to understand the commuting patterns of employees who participated in the Best Workplaces for Commuters (BWC) program. The goal of BWC is to reduce emissions and congestion by offering commuter benefits. Since the literature did not collect information regarding the proportion of survey respondents being coworkers, we assumed this value to be between 30% and 50%.

Our extrapolation shows that employees participating in this program could produce 1.59 percent (if 30 percent of the carpoolers were coworkers) to 2.70 percent (if 50 percent of the carpoolers were coworkers) less VMT compared to those who did not.

Logic Behind Policy Extrapolation from 2025 to 2045

To produce the VMT elasticities, we applied the following factors, based on the cited literature and stated assumptions. Table 14.27 below is a sample calculation with the percentage of coworkers set to 30%.

Table 14.27. Factors Needed for Carpooling Elasticities

Factors	Program Group	Reference Group	Source
Percentage of Coworkers	30%		Assumption
Occupancy	2.99	2.48	Herzog et al. (2006)
Total Persons	6,004		Herzog et al. (2006)
Drive Alone Persons	3,163	3,614	Herzog et al. (2006)
Carpool Persons	1,081	901	Herzog et al. (2006)
Drive / Carpool Mode Share	71%	75%	Herzog et al. (2006)
Drive Alone Trips	3,163	3,614	Herzog et al. (2006)
Carpool Trips	721	632	Extrapolation
Drive + Carpool Trips	3,884	4,246	Extrapolation
Other Trips	1,610	1,400	Extrapolation
Total Trips	5,494	5,647	Extrapolation
Average Commute Distance (Mile)	12.22		2017 National Household Travel Survey (NHTS) (McGuckin and Fucci., 2018)
Average Drive Distance (Mile)	12.71		2017 NHTS (McGuckin and Fucci., 2018)
Average Distance for Other Modes (Mile)	11.04	10.73	Extrapolation
Total VMT	69,624	70,749	Extrapolation

The VMT reduction estimate can then be derived using the formulas below:

$$Estimated\ VMT\ Reduction = (Elasticity\ for\ Employees) \cdot (\%\ Employees)$$

Using the percentage of employed population derived from ACS 2018, we find the adjusted VMT reduction over the baseline model for each place type, under the carpooling policy (see Table 14.28).

Table 14.28. VMT Reduction V.S. Baseline (Carpooling)

Place Type	$\%\ Employed$	$Elasticity_{employee}$	VMT Reduction (%)
Urban low transit	48%	-1.59%	-0.76%
Suburb with MF	44%		-0.70%
Central city urban	62%		-0.98%
Rural	39%		-0.61%
Suburb with SF	45%		-0.71%
Urban high transit	48%		-0.76%
Rural in urban	40%		-0.63%
Preserved	45%		-0.71%

The corresponding net VMT reduction per 5 years for each time frame is noted in Table 14.29.

Table 14.29. Per-Capita VMT Reductions Over Time (5-Year Changes) by Carpooling

	2025	2030	2035	2040	2045
VMT Reduction per capita	0.70%	0.00%	0.00%	0.00%	0.00%

14.2.3.8 Telework

During 2007 and 2008, the Chicago Metropolitan Agency for Planning (CMAP) conducted the Travel Tracker Survey of 10,552 households in northeastern Illinois to record their detailed travel behaviors in either a one-day or two-day period (CMAP, 2019). Employing the Travel Tracker Survey data, Shabanpour et al. (2018) [383] modeled the travel patterns impacted by home-based telework (i.e., an employment arrangement in which employees work from home). By assuming that employees with flexible schedules all worked completely from home, the model estimated a regional VMT reduction of 0.69 percent, if the percentage of teleworkers increased from 12 percent to 50 percent.

Two studies reported the direct impact of telework on the travel patterns of teleworkers only. Henderson and Mokhtarian (1996) [384] conducted an analysis on the effectiveness of the Puget Sound Telecommuting Demonstration Project. Home-based telework was found to reduce VMT by 66.5 percent, whereas center-based teleworking (i.e., a transportation control measure requiring employees to commute to a telework center rather than their worksites) could reduce VMT by 53.7 percent. Koenig et al. (1996) [385] assessed the impacts of home-based telework on the travel behaviors of participants in the State of California Telecommuting Pilot Project and found a 77 percent decrease in VMT. Neither of the two studies reflect a regionwide analysis because they did not take the proportion of employees or commuting frequency into consideration. However, they can provide a sense of how effective telework programs could be on reducing employee VMT.

Logic Behind Policy Extrapolation from 2025 to 2045

To develop the VMT elasticities, we applied the following factors, based on the cited literature and stated assumptions. Table 14.30 provides a sample calculation using the direct reduction rate of 66.5 percent (Henderson and Mokhtarian, 1996) [384].

Table 14.30. Factors Needed for Telework Elasticities

Factors	Explanation	Source	Value
Direct VMT Reduction	Percentage of VMT reduction per teleworker per day teleworked by personal vehicle	Henderson and Mokhtarian (1996)	-66.5%
% Employed	Percentage of population that are employed	ACS 2018 5-Year Estimates (USCB, 2018)	Varied by place type (see Table 14.23)
% Teleworkers	Percentage of employees that are required to telework	Brasuell (2020) and Gartner (2020)	Varied by place type (see Table 14.34)
Frequency	Days per week teleworked	Gartner (2020)	5 days per week
SOV Mode Share	Percentage of trips conducted in a single-occupancy vehicle (SOV)	ACS 2018 5-Year Estimates (USCB, 2018)	Varied by place type (see Table 14.33)

Table 14.21 ahows the rationale for deriving the percentage of the population that is employed. Additional sources come into play in helping us find the percentage of employees that are required to telework.

Plan Bay Area has proposed a telework policy (on any given workday) for large employers in the Bay Area. To build upon the significant shift to work from home during COVID-19, this proposed Plan Bay Area strategy mandates large employers have at least 60 percent of their employees telework on any given workday. This requirement would be limited to large office-based employers whose workforce can work remotely (Brasuell, 2020) [386].

The telework requirement on any given workday translates into a frequency of five days per week in our model. We apply this 60-percent assumption for telework across the populations of two place types: 1) central city urban and 2) urban high transit. Table 14.31 explains how this policy corresponds with our assumptions.

Table 14.31. Plan Bay Area Policy V.S. Assumptions Lookup Table

Plan Bay Area Policy Key Points	**Assumptions**
Large employers	The policy only applies to two place types (i.e., central city urban and urban high transit).
At least 60 percent of the employees	The percentage of teleworkers in central city urban and urban high transit is set to be 60 percent.
Any given workday	Given that there are five workdays in a week, the selected employees will telework five days a week over 51 out of the 52 weeks in a year.

According to a Gartner, Inc. survey of 317 chief financial officers (CFOs), about 74 percent of companies plan to permanently shift to more remote work after the COVID-19 pandemic. Approximately 27 percent of the CFOs said that they would remain 5 percent remote work, and another 25 percent would remain 10 percent (Gartner, 2020) [294]. This translates to the assumption that there is a range of 5 to 15 percent of teleworkers in both suburbs and rural areas.

These assumptions are populated in Table 14.32 for each place type.

Table 14.32. Percentage of Teleworkers by Place Type

Place Type	**% *Teleworkers***	**Source**
Urban low transit	15%	Gartner (2020)
Suburb with MF	15%	Gartner (2020)
Central city urban	60%	Brasuell (2020
Rural	5%	Gartner (2020)
Suburb with SF	15%	Gartner (2020)
Urban high transit	60%	Brasuell (2020
Rural in urban	10%	Gartner (2020)
Preserved	0%	--

Given that the 66.5 percent of VMT reduction only applies to SOV trips, we compute the SOV mode share from the ACS data collected in 2018 by taking the ratio of the total population who drive alone to work over the total employed population (see Table 14.33).

Table 14.33. SOV Mode Share (USCB, 2018)

Place Type	Number of People who Drive Alone to Work	Employed Population	SOV Mode Share
Urban low transit	4,995,351	6,497,260	77%
Suburb with MF	4,196,202	5,632,038	75%
Central city urban	83,693	313,988	27%
Rural	1,653,229	2,177,520	76%
Suburb with SF	5,368,423	6,963,155	77%
Urban high transit	1,127,031	1,936,698	58%
Rural in urban	748,402	1,038,957	72%
Preserved	116,941	157,257	74%

The VMT reduction estimate can be derived using the formula below:

$$Estimated\ VMT\ Reduction = (Direct\ VMT\ Reduction) \cdot (\%\ Employed) \cdot (\%\ Teleworkers) \cdot (Frequency)$$

The corresponding net VMT reduction per 5 years for each time frame is noted in Table 14.34.

Table 14.34. Per-Capita VMT Reductions Over Time (5-Year Changes) by Telework

	2025	2030	2035	2040	2045
VMT Reduction per capita	2.51%	0.00%	0.00%	0.00%	-0.01%

14.2.3.9 Shared Micromobility (Bikesharing and Scooter Sharing)

According to the North American Bikeshare Association (NABSA) (2020), user surveys have shown that about 36 percent of shared micromobility trips would have been made by automobiles if the shared devices were not available. The average trip in the year 2019 was estimated to be 1.3 miles long. Approximately 2.9 trips were made by a shared device in a day, and the number of vehicles per 1,000 people varied by city sizes, as shown in Table 14.36.

These statistics can yield an elasticity of -0.03% if compared with the baseline VMT model.

Logic Behind Policy Extrapolation from 2025 to 2045

To produce the VMT elasticities, we applied the following factors, based on the cited literature, as noted in Table 14.35.

Table 14.35. Factors Needed for Shared Micromobility Elasticities

Factors	Explanation	Source	Value
$Area$	The area of a region	TIGER/Line Shapefiles (USCB, 2019)	--
$FleetSize$	Number of shared devices in a region	Extrapolation	--
$Reduced\ VMT$	The annual VMT reduction in a region due to the shared micromobility adoption	Extrapolation	--
$TripDistance$	Average shared micromobility trip distance in miles	NABSA (2020)	1.3 miles
$\%\ CarTrips$	Percentage of shared micromobility trips that would have been made in an automobile	NABSA (2020)	36%

We defined $Vehicles/(1K\ people)$ as the average number of shared devices per 1,000 people and $Trips/Veh/Day$ as the number of trips made by a shared device in a day. Table 14.36 shows how the two factors vary across city sizes.

Table 14.36. Place Type Specific Shared Micromobility Factors (NABSA, 2020)

	Small Cities (Less than 200K people)	Medium Cities (200K–500K people)	Large Cities (More than 500K people)
$Vehicles/(1K\ people)$	2.30	1.75	1.10
$Trips/Veh/Day$	7	6	6

In our research analysis, the city sizes were mapped into the eight place types according to the following assignment (see Table 14.37).

Table 14.37. City Sizes vs. Place Types Lookup Table

	Small Cities (Less than 200K people)	Medium Cities (200K–500K people)	Large Cities (More than 500K people)
Urban low transit		✓	
Suburb with MF		✓	
Central city urban			✓
Rural	--	--	--
Suburb with SF	✓		
Urban high transit			✓
Rural in urban	✓		
Preserved	--	--	--

The VMT reduction estimate can then be derived using the formulas below:

$$FleetSize = (Vehicles/(Sq.Mi)) \cdot (Area)$$

$$Reduced\ VMT = (FleetSize) \cdot (TripDistance) \cdot (Trips/Veh/Day) \cdot (\%\ CarTrips)$$

The corresponding net VMT reduction per 5 years for each time frame is noted in Table 14.38.

Table 14.38. Per-Capita VMT Reductions Over Time (5-Year Changes) by Shared Micromobility

	2025	2030	2035	2040	2045
VMT Reduction per capita	0.03%	0.00%	0.00%	0.00%	0.00%

14.2.3.10 Subsidized Public Transit Passes for Low-Income

To make public transit more attractive and to enhance the mobility of a number of disadvantaged groups, transit agencies could expand programs that provide free or reduced-fare transit passes. Indeed, experience in California and elsewhere shows that free or reduced-fare transit passes have the potential to increase transit ridership, enhance the mobility of disadvantaged groups, and make it easier for children to go to school and participate in after-school activities. If they are sufficiently successful, these programs could also reduce traffic congestion and motor vehicle use, and consequently decrease vehicle miles traveled in personal vehicles.

A recent survey of California transit agencies [387] shows that most members of the California Transit Association (CTA) have free or reduced fare transit pass programs that target various groups. The most common programs are for students (from K-12 to university students) and for the elderly, but some of these programs also target employees of specific firms, low income travelers, people with disabilities, Medicare recipients, veterans, or simply residents of a city or a county. Most programs for the elderly also served people with disabilities.

While free or reduced fare transit pass programs almost always increase transit ridership, they may affect farebox recovery ratios, and to some extent the fiscal health of transit agencies. One exception is the “insurance model”, whereby all members of a large group agree to pay a relatively small fee to get the option to take transit for free during a set period of time, but only a subset of this group actually takes transit. In well-designed programs, this approach, which was extensively studied by Nuworsoo (2004) [388], increases both ridership and the revenues of the transit agency. It is typically used by learning institutions (such as colleges and universities) and employers (for example employees of San Francisco Airport). Interestingly, none of the California transit agencies who operate free or reduced fare transit programs based on the insurance program are losing money, according to the findings of Saphores et al. (2020) [387]. An alternative to the insurance model is to provide external funding to well-structured, well-monitored programs targeting groups with a limited ability to pay.

Unfortunately, California public transit agencies typically do not appear to know the detailed impact of these programs on their ridership, and even less on automobile use in the areas they serve. Overall, there appears to be a dearth of rigorous academic studies of free or reduced fare transit pass programs in the US.

A review of international experiences suggests that these programs can substantially increase transit ridership, although success stories may be difficult to replicate elsewhere, but their impact on decreasing car use is much more limited. For example, the city of Templin, Germany, saw a huge increase (750%) in public transit ridership when it made transit free to all riders around 2002, but only 10% to 20% of passengers had shifted to transit from cars, and up to 50% had shifted from walking [389]. Likewise, a system-wide fare-free program demonstration in Gaoping, a small (72,100 people in 2014) but dense Chinese city in Shanxi province, also saw a huge (320%) increase in public transit use, that overwhelmed the local transit agency [390]. Much of this increase came at the expense of walking, biking, and taxis, but the impact on private car traffic was limited.

Such increases are an exception, however. The well-known fare-free program in Tallinn, Estonia, which started in 2013, increased ridership by 14% a year after its creation, with a 40% modal shift from walking to public transit, but only a 5% percent shift from cars to transit [391], [392]. A study of the free bus program in Bergen, Norway, confirmed that while fare-free programs may substantially increase transit ridership, they are not very effective for getting people out of their cars [393]. Furthermore, the bump in ridership following the introduction of free or reduced fares may be diminishing over time [394], [395].

Free or reduced fare public transit programs can improve the mobility of various disadvantaged groups, however. For example, to make public transit more affordable to low-income people, in 2016 Toronto adopted the Fair Pass (FP) Program, which provided subsidized transit service to those receiving assistance under the Ontario Disability Support Program, or a Toronto Child Care subsidy. An analysis of the efficiency of the FP Program [396] found that ~60% of low-income Toronto residents were using this program and riding transit more than before the program began.

It is also worthwhile to mention a study of the potential benefits of a free transit program that would have been opened to all students (from preschool to college) in Los Angeles County (LAC). A study [397] of the potential benefits of this program estimated that providing unrestricted passes to all LAC students could increase transit ridership by 6 to 14 percent in the first 2 years, and by as much as 26 percent after 10 years (284,000 daily riders). It could also improve school attendance and have a number of health and other benefits. However, such a program has not yet been implemented.

Studies of the impacts of free or reduced fare public transit programs for the elderly are also very limited in the US [387]. As a point of reference, we will simply mention that a 2006 measure in England, which introduced a free full fare program in replacement for a half-fare program for adults aged 60 and above saw an 8.3% increase in bus ridership [398].

Given these limited data, we assumed that generalized free transit programs for high school and college students in California and for adults over 60 could decrease daily trips by 20% for both the former and by 10% for the latter. We assumed that high schools and universities would put in place appropriate pricing measures (e.g., substantially increase the cost of parking on or close to campuses). We also assumed that organizations such as the AARP would encourage seniors to leave their automobiles at home and that public transit would partner with TNCs (or extend paratransit) to provide more point to point service for senior citizens. Future studies should investigate the incentives needed to make this happen.

In closing, we would like to emphasize that we should not ask too much from these programs. While well-designed programs can increase transit ridership and enhance the mobility of selected groups, other goals may prove elusive if these programs are used in isolation. For example, programs intended to reduce motor vehicle use will likely need to be coupled with measures to increase the overall cost of driving (such as cordon pricing, road pricing, parking pricing, as well as increased fuel and vehicle taxation), as highlighted in Saphores et al. (2020) [387].

14.2.4 Equity

It is important to consider the implications for equity of promoting more compact forms of development. On one hand, such an approach offers financial benefits for lower-income households. U.S. households spent an average of $8,132 on their cars in 2016 [399]. Across the income spectrum, transportation accounts for almost 16 percent of all spending for households, though the burden is far greater for low-income households. Sixty-four percent of households with annual incomes under $20,000 own a car, despite the substantial cost, and sixty percent of households below the poverty level feel that transportation is a financial burden [400]. In communities with good regional transit connections and accessibility to jobs and amenities households have the potential to reduce transportation costs by reducing driving [401]–[403]. Money saved by driving shorter distances or switching to active modes could be spent on other important household needs.

But efforts to change existing neighborhoods by increasing densities and improving infrastructure raise concerns over potential gentrification and the displacement of existing residents. Many cities have seen a strong connection between densification and gentrification, but the direction of causality is not always clear. Infill development can directly displace current residents and lead to rent increases that further displace residents. But gentrification can also precede infill development, creating the kind of market dynamics that make infill projects attractive to developers. With the right policies in place, it may be possible to encourage infill development, particularly around transit stations, without exacerbating gentrification pressures [404]. Communities might adopt policies to minimize physical displacements and limit rent increases for current residents, as well as policies that ensure that infill developments include—or pay for—enough affordable housing to offset losses. The role of public investments such as rail systems must also be considered: such investments could be paired with policies to ensure that those who would most benefit from access to high quality transit have the opportunity to live near them.

Additional questions:

1. If passenger vehicles largely account for VMT on US roads, are there strategies or policy incentives to provide alternative transportation options in low-income communities that do not provide substantial public transit or active mobility infrastructure?
2. Are there impact studies that specifically look at shared mobility options for persons with disabilities? Is this population represented in the carsharing impact studies?
3. If carsharing reduces vehicle ownership and VMT, is this a viable transportation option for persons with disabilities? Are there programs or incentives for carsharing fleets to provide accessibility for this population (e.g., fleet modifications)?

14.2.5 Conclusion

A complex set of policies across all types of VMT reduction categories is clearly needed to achieve the LC1 scenario target of a 15% reduction by 2045 in per-capita VMT in California. All of the examined strategies and policies across several categories of VMT reduction will be needed at some level to achieve this, with some flexibility in achieving the 15% and perhaps higher goals through especially the level of implementation of pricing policies. However, achieving any of these ambitious VMT reduction targets will necessarily require improvements in public transit, micromobility, active transportation and other low-carbon modes to provide sensible transportation alternatives and to reduce equity impacts on lower income populations.

14.3Fuel Appendix: Model Design and Methodology

The fuel model described in this study was designed around the capabilities, resources, and limitations of this study in mind. Given the presence of several other research groups who brought to the group their own tools, models, and perspectives, and given the extremely short timeframe under which this work was completed, we adapted the fuels model to the scenarios and outputs of the other teams (e.g., Light-Duty Fleet, Heavy-Duty Fleet, VMT, etc.) rather than being a primary driver of change in the scenario modeling. Under a perfect scenario, all constituent models would be fully integrated into a single modeling framework, allowing data to flow between them and for the outputs of one to affect another. For the purposes of this study, the evidence on interactions between fuels, vehicles, and policy indicate that fuel availability, carbon intensity, and price are likely to be relatively smaller drivers of change than vehicle price, vehicle capabilities, and policy choices.

Accordingly, the model described herein is purely descriptive; it does not perform any optimization or simulation on its own. Its purpose is to automate the extremely complex task of tracking the many fuels that constitute California’s transportation fuel portfolio, allowing simple manual projections and scenario analysis, and relatively easy identification of areas where a given scenario or fuel portfolio produces infeasible results. Examples of such identified infeasible areas would be production of fuels in excessive or negative amounts or with unrealistic characteristics, non-compliance with statutory or administrative targets, or a mismatch between fuels and vehicles. The model is also intended to allow rapid scenario analysis with as much transparency and flexibility as possible.

This model is an Excel 2016 workbook and draws heavily from two previous models, which were the basis for the *California’s Clean Fuel Future* (*CCFF*) report and CARB’s *Illustrative Compliance Scenario Calculator* (August 15, 2018 version, abbreviated “ICSC”). The model, in fact, includes parts of the ICSC and outputs from *CCFF* in the Excel spreadsheet, though they are included for illustrative and reference purposes only and are not programmatically linked to the fuels model developed for this study. The model takes as input several output tables from the Transportation Transitions Model (TTM) and numerous manual inputs from the operator, and outputs a variety of fuel quantities, carbon intensities, and other data, as well as several graphs. While this model was not fully integrated with the TTM or any of the other models that inform the results of this study, there was regular interaction between the author of this model (Dr. Murphy) and Drs. Marshall and Fulton, who developed the TTM and ran the scenarios for this project. This served as an ad-hoc integration of the two models, as both informed the development of the structure and scenarios in the other.

Based on guidance from CalEPA and CARB, this report attempted to treat fuel modeling in a similar fashion to how it is treated by the LCFS, using CI scores, credit calculation methods, and analytical frameworks based largely on that of the LCFS. [405]

This appendix will walk through the various (Excel) sheets in this model to describe and document the underlying analytical assumptions as well as offer guidance for future users.

14.3.1 Control Panel Tab

This tab is intended to be a single location for variables and input data that will affect the model in multiple places. While the calculation sheets for any scenario can be manually changed, doing so is recommended only where the desired input cannot be made through the Control Panel tab because manual changes in the calculation tab can be difficult to identify and find later, leading to unwanted inputs propagating between scenario runs and contributing to inaccurate results.

For the majority of fuels considered in this study, there are few, if any, credible projections of fuel volumes or carbon intensities after 2030. There are, however, several projections of fuels to 2030, most of which are cited by and integrated into the *California's Clean Fuel Future* report (*CCFF*). Fuel volumes, for this study, are generated by the Transportation Transitions Model (TTM), which solves for lowest-cost compliance scenarios, including vehicle and operational costs. This model identified several areas where constraints on fuel supply would affect the fuel portfolio and those were integrated into the TTM. Unless otherwise noted, fuel carbon intensities are taken from the *CCFF* for years 2017-2030. Thereafter, fuel carbon intensities decline by a fixed percentage each year. The percentages were selected to yield a fuel portfolio judged by the study team to be compliant with the 2045 carbon neutrality goal as established by Executive Order B-55-18. In the case of the central low-carbon scenario (LC1), this meant total emissions below 5 million tonnes per year, which was judged to be well within the capability of likely CCS deployment to offset. As such, the CI improvement rates should be viewed as targets for fuels policy rather than as predictions of future behavior.

The percentages that yield this outcome are described in Table 14.39. The year-on-year CI decline generally exceeds those observed in similar industries to date; our expectation would be that incremental CI reductions would occur at a slower pace, but that advanced new fuels would enter the market, displacing older, higher-carbon fuels and yielding significant reductions in CI. As such, the percentage decline should be viewed as a long-run average, not a prediction of year-to-year performance.

Table 14.39. Carbon Intensity improvement rates for various fuels, under the BAU and LC1 scenarios

Fuel	BAU CI Improvement Rate	LC1 CI Improvement Rate
Starch/Sugar Ethanol	3%	4%
Cellulosic Ethanol	4%	6%
Biodiesel Post-2030	3%	4%
Renewable Diesel Post-2030	3%	4%
Assumed RNG Post-2030	3%	4%
Drop-In Gasoline / Naphtha	6%	6%
SAF	6%	6%

Other parameters controlled from the control panel are presented in Table 14.40.

Table 14.40. Other parameters controlled from the Control Panel

Parameter	Value	Source or Rationale
Cellulosic Ethanol Post-2030 Volume Growth	10%	Set to attain 2045 target
Biodiesel Blend Rate	6%	Based on 2015-2019 LCFS Data
Assumed Low-Carbon Electricity CI	0%	Assumed to be 100% Renewable
Assumed Fixed Guideway Pre-2030 Growth Rate	1%	Based on 2015-2019 LCFS Data
Assumed Fixed Guideway Post-2030 Growth Rate	3%	Assumed higher due to HSR
Assumed OGV/eFork/eCHE/eTRU Growth Rate	3%	Based on 2015-2019 LCFS Data
Pre-2030 Ethanol as fraction of liquid gasoline pool	11%	Based on 2015-2019 LCFS Data
Post-2030 Ethanol as fraction of liquid gasoline pool	16%	Assumed blend wall increase to 15%
Naphtha fraction of RD for Co-processing to gasoline	5%	Input from refiners
Renewable Propane as Fraction of RD	4%	Dept. of Energy & Climate Change (2014) [406]

For parameters not modeled by the TTM or provided by other working teams, estimates of yearly growth were taken from recent LCFS program data and assumed to continue at the same rate.[407] Additional research is warranted to better understand likely growth rates for these parameters, but in general they had little impact on the core outcomes reported in this study. While the ethanol fraction, more commonly known as the "blend wall," is nominally 10%, the presence of a small number of E85 vehicles increases the aggregate ethanol fraction, by volume, by almost 1%. We assumed that this additional percentage point of ethanol consumption above the blend wall would persist through the duration of this study.

All scenarios, including the business-as-usual (BAU) assume a blend wall increase to 15% no later than 2030 (modeled as a single step to 2030 in all scenarios). This reflects recent regulatory progress towards increasing the blend wall by the Environmental Protection Agency. In all scenarios compliant with the 2045 carbon neutrality target, the net quantity of ethanol consumed by California had declined significantly by 2030, due to declining petroleum gasoline consumption. The blend wall increase only partially restored the lost ethanol consumption. In the BAU case, the blend wall increase led to peak ethanol consumption occurring in the early 2030s, peaking at around 6% higher than the previous peak in 2017. Note that from the model's perspective, the critical change is a shift in ethanol consumption as a fraction of gasoline consumption. This shift could occur by a number of mechanisms other than an adjustment to the blend wall, including increased sales of high-ethanol fuel blends such as E85 (which contains 50-85% ethanol) or 20-30% ethanol blends, which have been proposed by automakers as an enabling measure for more-efficient, higher-compression internal combustion engines.

There is significant uncertainty in the literature regarding the amount of naphtha produced as a coproduct during renewable diesel processing, with values ranging from 4% to 18%. While most published sources tended towards the higher end of that range, conversations with refinery stakeholders indicated that in practice, the volume is much lower. The naphtha co-produced in RD refining is of relatively low quality and would have a significantly lower value than the intended RD product. Refiners would be expected to optimize their production process to minimize the lower-value coproduct, and so values at the lower end of the range were selected based on the input from stakeholders.

14.3.2 TTM Output Preprocessing

TTM categorizes vehicles based primarily on their weight class (light-duty vs. medium- and heavy-duty), whereas the LCFS uses a categorization system based primarily on the conventional benchmark fuel used by the class of vehicles, that is, whether a vehicle uses gasoline and gasoline substitutes, or diesel and diesel substitutes. Weight classes largely overlap with fuel classes since medium- and heavy-duty vehicles are predominantly fueled by diesel at present, while light duty ones use gasoline. There are some mismatches between these classification systems, however; for example, the TTM classifies heavy-duty (HD) pickup trucks (generally DOT Class 2B) as heavy-duty vehicles, but they are classified as light-duty by CARB for the purpose of assigning energy economy ratios. A preprocessing step was added to rectify this mismatch, in the "Input Data" tab. Raw tabular outputs from the TTM fuel consumption tabs were copied, including aggregate light-duty, aggregate heavy-duty, and heavy-duty pickups. The class-specific outputs for HD pickups were then subtracted from the TTM aggregate heavy-duty output and added to the light-duty output. The fraction of diesel consumed by HD pickups was also calculated and used to assign the appropriate amount of biodiesel to the light-duty category as well. However, all LCFS credit generation from diesel substitutes was estimated using diesel as the benchmark fuel for comparison. This ensured that displacement of diesel by electrification of HD pickups generated credits using the appropriate energy economy ratio.

14.3.3 Maximum Lipid-based Distillate Constraint

During the long-term modeling of fuel pathways, total consumption of non-fossil lipids (non-fossil oils) emerged as a critical concern. Renewable diesel and biodiesel have emerged as large-scale, cost-effective substitutes for petroleum diesel, resulting in significant reductions in GHG and modest reductions in other pollutants. While current renewable diesel and biodiesel production pathways do not achieve carbon-neutral life cycle emissions, they can yield 50–75% reductions in GHGs and presumably would continue to incrementally improve over time.

These fuels do come with some significant concerns. Of prime concern (for the purposes of this study) are the impacts of indirect land use change (ILUC). ILUC is the subject of significant and intense debate within the biofuel and land use research communities. While there is still significant uncertainty around quantifying the impact of ILUC on life cycle GHG emissions, a consensus among researchers supports the conclusion that ILUC is real and can potentially cause large GHG impacts [408], [409]. The LCFS accounts for ILUC by assigning an ILUC factor to fuels which are derived from feedstocks strongly associated with exacerbating ILUC. These factors are developed using the Global Trade Analysis Project (GTAP) and Agro-Economic Zone (AEZ) models for international agricultural commodity markets and agriculture-driven land use change impacts, respectively.

At present, most models and stakeholders distinguish between fuels made from wastes or residues, such as used cooking oil, tallow from meat processing, or inedible corn oil from ethanol production, and those made from oilseed crops, such as soybean, palm, or canola. Waste- or residue-based fuels are typically assumed not to cause ILUC. While waste or residue based fuels are less likely than crop-based fuels to cause ILUC and related impacts on GHG emissions, emerging evidence indicates that the former are not completely free of ILUC and its GHG impact. There are many potential uses for waste or residue lipids, including as ingredients in animal feeds, cosmetics, or other bioproducts. Recent evidence indicates that many of the processes that customarily use waste or residue lipids do so because of low cost, not technical requirement. If waste or residue lipids are unavailable, they will use crop based oils instead, which leads to a similar outcome as when edible oils are used for fuel instead: the demand for additional oils leads to conversion of land to oilseed production, which is the core driver of ILUC. There is growing empirical evidence of this substitution as well [409]. With future policy likely to continue increasing demand for low-carbon fuel substitutes, the assumption of zero ILUC from waste based fuels needs to be reexamined.

ILUC is a dynamic concept and likely varies spatially and temporally. There is substantial uncertainty around present-day estimates of ILUC. Attempting to forecast it over the time horizon of this study would require significant advances in modeling, as well as access to proprietary data. This presented a dilemma to the modeling team. ILUC was clearly a significant factor affecting long-term potential biofuel production volumes and the life cycle GHG impacts of each, but an accurate projection was beyond the capacity of current modeling tools, as well as the scope of this study. Future research will be required to address this issue, to both improve quantitative estimates of ILUC and its impact on GHG emission as well as develop “next-best” approaches to mitigate ILUC impacts where quantification is impossible.

For the purposes of this study, we followed the approach of both the *CCFF* study and CARB in their modeling during the 2018 LCFS re-adoption proceeding: Ensuring that the maximum amount of lipid-based fuels did not exceed an aggregate level judged to be below that likely to cause unacceptable ILUC impacts, with a significant margin for safety. By design, most projections in the *CCFF* did not exceed 1.5 billion gallons/year of fuels from lipids, while CARB’s ICSC did not exceed 1.7 billion gallons/year. In the interests of making a conservative assumption, we assumed a “maximum” of 1.5 billion gallons/year of lipid-based alternative fuels.

This volume constraint on lipid-based diesel and aviation fuels is not, nor is it intended to be, a proxy for an absolute market or resource based constraint on the total volume of such fuels that could be brought to California through 2045. There are, in fact, few if any absolute constraints on the total amount of lipid-based fuels that could come to California. There are a number of projects under development that will yield aggregate capacity to more than replace all diesel fuel used in California and the strong incentive provided by the LCFS means that California will likely be one of the most attractive markets for such fuels. The limitation to 1.5 billion gallons/year is meant to reflect a desire that California not precipitate unacceptable levels of ILUC through its policy. If biodiesel (BD) and renewable diesel (RD) volumes continue to grow through the early 2020s at rates along the upper end of likely projections, California may need to consider enhancing its policies to limit ILUC from the increased demand on global vegetable oil supplies. Options for this could include modifying the types of fuels subject to an ILUC charge or the amount of that charge, enhanced sustainability requirements for lipid based fuels, or limiting the maximum amount of such fuels which are eligible for LCFS credits in a given year. The purpose of the 1.5 billion gallon/year limitation is to ensure that trajectories for decarbonization are not reliant on unsustainable levels of oilseed production and the choice to apply a volume limitation was largely a reflection of the complexity involved in applying other mechanisms to this model.

With the maximum aggregate amount of lipid-based fuel established, the next step is to allocate it among the potential fuels, BD, RD and sustainable aviation fuel (SAF). At present, all three fuels are being consumed in California and generating LCFS credits and all expect to grow. In practice, the allocation among these fuel pathways would be determined by market and technological forces. Future work at the UC Davis Institute of Transportations Studies is aimed at developing a model that would more precisely evaluate these factors to determine the distribution of fuels. For the purposes of this study, a simple heuristic was developed to handle allocation, which followed the following steps.

1. SAF demands were satisfied first. This was based on the assumption that, as the sector with the fewest viable alternatives to liquid hydrocarbons as fuel, SAF producers would have the greatest long-term need and likely the highest ability to pay, especially after more cost-effective alternatives are developed for on-road transportation.
2. Next, biodiesel sufficient to yield the user-specified blending level was subtracted from the remaining potential capacity. It was judged that biodiesel blending would continue at this level and to that limited extent, have priority over RD production because BD is a slightly cheaper and lower-carbon fuel to produce than RD. At blends above the baseline biodiesel blending level, problems with engine performance or cold-weather flow can emerge. Since there is a significant amount of biodiesel production capacity already operational, it was assumed that this would continue to operate in order to satisfy baseline biodiesel blending, but additional growth in diesel substitutes beyond this level would be concentrated in RD pathways.
3. Once SAF and BD uses had been satisfied, the residual volume was assumed to be converted to RD, with a small amount of renewable propane and naphtha co-product. Based on the number of RD capacity projects that have been announced, it was judged that there would be sufficient production capacity to satisfy this demand.

It must be emphasized that this is a rough heuristic used to facilitate the high-level and long-term modeling exercise of this study. It is not meant to be a quantitatively accurate projection of future behavior. In addition, there is a certain degree of fungibility between these different fuel pathways. Many production pathways based on hydrotreating vegetable or waste oil typically produce both SAF and RD, with a limited capacity to shift the process to emphasize one fuel or the other. There may also be non–oil-based feedstocks that can affect the assumptions about resource availability, as well as other pathways that may yield a mixture of fuels, or the capacity to change product slates by altering operational parameters. Two projects are under development to produce SAF from cellulosic waste materials, which would yield SAF that avoids the ILUC impacts of lipid-based fuels. Some of the advanced biofuel pathways described by this model may use feedstocks which have little ILUC risk; alternatives based on more sustainable feedstock could displace some of the first-generation fuels anticipated here and such fuels would not be subject to a limitation on the use of lipid derived fuels intended to limit ILUC risk. In general, this model assumes minimal development of cellulosic or advanced fuels and highlight the need for them by describing their absence, rather than projecting actual development.

SAF demand was approximated as the amount of fuel needed to support intra-state commercial and general aviation, since interstate and international flying is protected from state level regulation by Federal law and international treaties (though SAF used in interstate or international flights can generate LCFS credits as an opt-in fuel). Following the guidance of other state policies, emissions from military and first-responder uses were also excluded from this study. Recent statewide fuel consumption for intra-state flights was not found during the literature review, so the emissions from the aviation category in the 2017 GHG inventory were used to derive a proxy by dividing them by the carbon intensity of jet fuel, on a tank-to-tail basis (excluding upstream emissions).[324] Growth in this consumption was estimated by using passenger trip growth factors estimated from California Transportation Demand Model v2 data. We aggregated all intrastate trips in the aviation category for 2020, 2035, and 2040 and interpolated between those years to yield a 2.5% growth rate through 2035 and a 0.9% growth rate thereafter. Growth in the number of trips is at best a very rough approximation for growth in intra-state fuel consumption. CARB or the California Energy Commission may be able to assist long-term planning by tracking fuel consumption in this category. We then applied a 1.4% per year improvement in fuel economy based on ICAO estimates of global average aircraft fuel economy improvement.[410, p. 204] This yielded SAF consumption in the 500-600 million gallon/year range over the study period. General aviation fuel demand was estimated as a fraction of jet fuel based on the ratio of general aviation emissions to commercial, that ratio was assumed to hold through the time period evaluated in this study.

The model subtracted yearly SAF from the available lipid-based fuel maximum quantity to estimate the amount of oil feedstocks remaining for on-road fuels. This essentially assumes that SAF would take first cut of potential feedstock coming into the state. We emphasize that the real fuel and feedstock portfolio will likely be more variable and complex. Since there is a significant degree of fungibility between SAF and RD, as well as other advanced biofuels, and a severe scarcity of credible projections of long-run fuel production, this assumption serves as a viable proxy for long-term behavior in the lipid-based biofuel space but should not be interpreted as a prediction of actual market behavior.

Once SAF was considered, the residual lipid-based fuel volume was allocated between BD and RD. It was assumed, based on current market trends and consultation with stakeholders, that most of the growth in biomass-based diesel substitutes would come from RD, due to its ability to be freely blended with conventional diesel and used in all engines, and its superior cold-weather performance and better NOx emission characteristics. We assumed that the existing BD production capacity would continue to produce sufficient BD to continue blending at the current average blend level of 6%, and that BD would be blended into RD and petroleum diesel at that level [407].

Total BD consumption was therefore estimated as 6% of the total volume of all diesel and liquid diesel substitutes forecast by the TTM. The remaining lipid feedstocks were used to produce RD. This yielded 800-900 million gallons/year of RD. Early runs of the TTM projected a higher consumption of RD, so an appropriate constraint was added to limit total consumption. BD and RD consumption for heavy-duty pickups was then calculated and moved from the heavy-duty category to light-duty to correct for the difference in vehicle classification between the TTM and LCFS.

14.3.4 Estimation of Renewable Natural Gas Source and Carbon Intensity

The TTM included categories for liquefied natural gas (LNG) and compressed natural gas (CNG) in the heavy-duty vehicle category, and CNG only in the light-duty category. The TTM makes no distinction between fossil natural gas and RNG. To accurately assess total emissions, estimating the share of various feedstocks used to make RNG is necessary. This operation is separated into an "RNG" tab in the model. It compares total RNG demand, as projected by the TTM, against total potential volumes of RNG from various feedstock categories. A study on long-term U.S. RNG potential done by ICF, for the American Gas Foundation was used as the basis for estimating the potential U.S. RNG resource [310]. California was assumed to be limited to a population-weighted share of the total U.S. resource. It should be noted that given California's significant head start on climate and fuel policy, it would likely be one of the most attractive markets for RNG, using the book-and-claim accounting method, which allows for RNG from any project in the U.S. to sell into the California market by injecting their gas into a common-carrier pipeline, whether or not the physical gas is itself conveyed to California. So, this estimate is likely to err on the conservative side regarding both aggregate quantity of RNG available as well as the carbon intensity of that which is sold into the state.

To estimate California's RNG supply by source, we condensed the categories reported in the American Gas Foundation report down to three that matched those reported in LCFS data: livestock, landfill, and organic waste. Livestock and landfill were taken directly from the AGF report, wastewater treatment, food waste, and organic MSW were aggregated into a third category. Agricultural residues and other feedstocks converted by thermal methods were assumed to be used for purposes other than producing RNG for transportation. The report's conservative "Low-resource" scenario was used as the basis for estimating the amount of RNG available to transportation projects. While this may under-estimate the total amount of RNG available, the conservative estimate is warranted due to the many other sectors that may use RNG to reduce emissions [411].

Estimating the carbon intensity of this RNG supply requires adjusting for long-term changes in the GHG accounting associated with RNG and avoided methane. At present, many sources of feedstock used to produce RNG would otherwise decompose naturally and release substantial amounts of methane, a potent GHG. RNG projects that prevent this fugitive release can claim credit for the averted warming and reduce the CI of their resulting fuel accordingly. This avoided methane credit does not last forever, once regulation or industry normal practices would otherwise control the methane release it is no longer appropriate to credit it to the RNG project. CARB guidance on avoided methane credit indicates that the credit can be claimed for the full 10 years of a pathway certification, as long as the project began operation before any regulation required control of methane emissions. This means that RNG projects selling into the California market can maintain the avoided methane for potentially as much as 10 years after regulations requiring methane abatement come into effect.

CARB has adopted the Short-Lived Climate Pollutant Strategy, which requires a significant abatement of fugitive methane, including from livestock yards. Anaerobic digesters convert organic matter like animal manure into RNG and digestates that can be used as soil amendment. These digesters are expected to be commonly used for compliance with fugitive methane reduction requirements, and are typically well suited for application in livestock manure management. Implementation details of the Short-Lived Climate Pollutant Strategy have not been fully developed, but under current reading of the regulations, and based on consultation with CARB staff, it appears likely that compliance will be mostly accomplished by 2025. RNG carbon intensities must therefore account for the termination of this avoided methane credit in the early 2030s.[27] This predominantly affects RNG generated from livestock operations. We assumed that the overwhelming majority of such digesters would be build between 2020 and 2025, and as such, would lose their avoided methane credit over the 5 years between 2030 and 2035. Carbon intensities for livestock anaerobic digestion systems were based on ICSC values through 2030 and then phased down to match those of organic waste digesters, without an avoided methane credit over that time.

Phasing out the avoided methane credit does not indicate the loss of preferential treatment for livestock digesters or an intentional policy change to reduce their presence in the fuel portfolio. The avoided methane credit can best be thought of as assigning emissions reductions that physically occur within the agricultural sector—at a livestock yard, for example—to a project classified in the transportation sector, for GHG accounting purposes. This aligns with current guidance on life cycle analysis, but requires that the agricultural sector continue to report the fugitive methane in GHG inventories to avoid double-counting the reduction. That is to say, if the transportation sector claims credit for reducing agricultural sector emissions, then the agricultural sector cannot claim credit for reducing the same emissions. At some point, if California is to achieve its long-run climate goals, the agricultural sector will have to reduce its emissions as well, so continuing to have large fugitive methane emissions on its books would become problematic. As such, a finite duration for such avoided methane credits comports with the good GHG accounting practices.

The TTM projections of natural gas consumption indicate that California is unlikely to consume its full “share” of total U.S. RNG, even under the conservative assumptions of total resource made in this study. RNG vehicles may struggle to achieve long-run carbon neutrality, since without the avoided methane credit, the CI of produced fuel was in the 15–25 gCO_2e/MJ range in 2045, assuming a 3% per year improvement in CI. This represents a significant improvement over petroleum diesel but would require additional improvement beyond the yearly incremental improvements to contribute to a carbon-neutral transportation system. This aligns with similar findings from other studies (e.g., [412]), that RNG offers short-term emissions reduction opportunities, but limited value as a transportation fuel over the long-term unless it is processed in a way that allows its embodied carbon to be sequestered, or achieves much higher efficiencies than possible in an internal combustion engine.

Since the total consumption of RNG would often be below the maximum potential during the time period examined in this study, the model allocates RNG sources in order of ascending carbon intensity, that is, RNG from livestock digesters is assumed to be preferentially used first, followed by organic waste digesters, and then

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[27] A formal sensitivity analysis around the impacts of different schedules for phasing out the avoided methane credit was beyond the scope of this study. The research team performed an informal evaluation of acceleration or delay in the phase-out period and observed no significant difference in long-term outcomes.

any residual is supplied by landfill gas. The model processes this hierarchy of demand, and then determines a yearly average CI for all RNG used, which is the basis for RNG CI calculations in the model.

14.3.5 Other Input and Output Tabs

Several other tabs and data tables have been created to simplify the process of making changes to critical parameters, to ensure that analytical assumptions are maintained across scenarios where desired, and to simplify the process of comparing results across scenarios. These tabs include:

Carbon Intensity – Labeled "CIs," this tab has a set of year-by-year CI trajectories for fuels in which the CI is not calculated elsewhere. By default, the CI trajectories generally follow CI trajectories from the California Clean Fuel Future report (*CCFF*) or *Illustrative Compliance Scenario Generator* (ICSC) through 2030, and then a constant percentage reduction thereafter, representing continued incremental improvement. These can be manually modified to create scenarios, though if CI trajectories for any fuel are meant to differ between scenarios, they may need to be manually adjusted in the scenario calculation sheets.

These carbon intensities, reproduced in Table 14.41 and Table 14.42, represent averages across all examples of a given fuel type within the system, rather than a specific fuel or feedstock pathway. While they are all technologically plausible, they are as much targets or necessary milestones as they are predictions of actual behavior. By design, California's fuel policies offer flexibility for stakeholders and end users to determine the optimal route to compliance, and excess emissions by one fuel or pathway could be counteracted by high achievement of others.

Fuel Volumes – This sheet reports fuel volumes for all tracked fuels in gasoline gallon equivalents (gge), in order to simplify comparisons.

Emissions - This sheet reports life cycle GHG emissions for each fuel pathway, as well as a sum across all pathways.

Table 14.41. Model Default Carbon Intensities (g/MJ). Generally taken from California's Clean Fuel Future or the Illustrative Compliance Scenario Generator. Shaded cells indicate those based on historic LCFS data, all others are projections or assumptions. Hydrogen carbon intensity taken from [413]

		2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Grid Average Electricity	g/MJ	105.2	81.5	82.4	82.9	79.6	76.3	73.0	69.7	66.3	63.0	59.7	56.4	53.1	49.8
Average Hydrogen	g/MJ	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	93.2	78.3	63.4	48.5	33.6	18.7
Conv. Starch Ethanol	g/MJ	70.6	68.0	62.0	62.0	62.0	62.0	61.0	60.0	59.0	58.0	57.0	56.0	55.0	55.0
Sugar Ethanol	g/MJ	37.8	35.8	34.0	32.5	30.8	29.2	27.7	26.4	26.5	26.6	26.8	26.9	27.0	27.1
Cellulosic Ethanol	g/MJ	50.0	50.0	50.0	50.3	49.4	48.5	47.6	46.7	45.8	44.9	44.0	43.1	42.2	41.3
Renewable Diesel	g/MJ	34.1	31.0	35.6	34.0	33.0	32.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
Biodiesel	g/MJ	30.4	32.2	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
SAF Average	g/MJ			35.6	34.0	33.0	32.0	31.0	31.0	31.0	29.1	27.4	25.7	24.2	22.8
Drop-in Bio-Gasoline	g/MJ	35.0	32.9	30.9	29.1	27.3	25.7	24.1	22.7	21.3	20.1	18.9	17.7	16.7	15.7
Renewable Naphtha	g/MJ		53.8	54.6	57.1	53.7	50.5	47.4	44.6	41.9	39.4	37.0	34.8	32.7	30.8

Table 14.42. Carbon Intensities (g/MG) common to all scenarios, 2031-2045

		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Grid Average Electricity	g/MJ	46.4	43.1	39.8	36.5	33.2	29.9	26.5	23.2	19.9	16.6	13.3	10.0	6.6	3.3	0.0
Average Hydrogen	g/MJ	22.7	26.7	30.7	34.7	38.7	37.1	35.5	33.8	32.2	30.6	25.2	19.7	14.3	8.9	3.4
Conv. Starch Ethanol	g/MJ	52.8	50.7	48.7	46.7	44.8	43.1	41.3	39.7	38.1	36.6	35.1	33.7	32.4	31.1	29.8
Sugar Ethanol	g/MJ	26.0	25.0	24.0	23.0	22.1	21.2	20.3	19.5	18.8	18.0	17.3	16.6	15.9	15.3	14.7
Cellulosic Ethanol	g/MJ	41.3	38.8	36.5	34.3	32.2	30.3	28.5	26.8	25.2	23.7	22.2	20.9	19.7	18.5	17.4
Renewable Diesel	g/MJ	30.1	29.2	28.3	27.4	26.6	25.8	25.0	24.3	23.6	22.9	22.2	21.5	20.9	20.2	19.6
Biodiesel	g/MJ	26.2	25.4	24.6	23.9	23.2	22.5	21.8	21.2	20.5	19.9	19.3	18.7	18.2	17.6	17.1
SAF Average	g/MJ	21.4	20.1	18.9	17.8	16.7	15.7	14.8	13.9	13.0	12.3	11.5	10.8	10.2	9.6	9.0
Drop-in Bio-Gasoline	g/MJ	14.7	13.8	13.0	12.2	11.5	10.8	10.2	9.5	9.0	8.4	7.9	7.5	7.0	6.6	6.2
Renewable Naphtha	g/MJ	28.9	27.2	25.5	24.0	22.6	21.2	19.9	18.7	17.6	16.6	15.6	14.6	13.8	12.9	12.2

14.3.6 Calculation Tabs

Most of the functionality provided by this model occurs in the “Calculations” tabs. The default version of this model includes three calculation tabs for the BAU, Low Carbon (LC1), and high-ZEV (ZEV) scenarios. Additional scenarios can be added by copying additional instances of the calculation tab and making appropriate modifications. Note that relative cell references were used in many cases, so accurate functionality cannot be guaranteed if rows or columns are added or removed from the worksheets.

The calculations tabs take the fuel consumption projections from the TTM, adjusted to move HD pickups into the light-duty category. These are replicated in rows 6-25. The calculation tabs also include aggregate fossil fuel consumption, aggregate non-fossil fuel consumption, and the average CIs for the gasoline and diesel pools, in line 29-34.

Due to the challenges of maintaining stability in the LCFS market during the period of rapid expansion of ZEVs, credit generation for ZEVs was phased down to zero from 2037 to 2043 for light-duty vehicles and from 2039 to 2043 for heavy-duty vehicles in the LC1 and ZEV scenarios (See section: 9.4.3.1). This was accomplished by using the ZEV credit adjustment, which reduced total EV credit generation by a specified amount, in lines 41 and 42.

The model tracks LCFS credit and deficit generation to determine approximate credit balance over time, with total fossil fuel deficits reported in line 44. Incremental crude deficits, which reflect the gradual shift towards heavier, more carbon-intensive sources of crude oil, are reported in line 45. Forecasting the future crude oil portfolio for California refineries is beyond the scope of this model and this report, so estimates from the CARB ICSC were used through 2030, and thereafter reduced in proportion to the decline in total fuel energy coming from petroleum.

LCFS credits were calculated in fuel-specific sections of the calculation tab, and the total credit or deficit generation was brought into lines 50-60, with a yearly sum and estimation of the aggregate credit bank below.

14.3.6.1 Ethanol Calculations

The TTM aggregates most alternative liquid fuels into a single category, so all gasoline substitutes—presently only ethanol, but drop-in gasoline in the future—are reported as a single category. Because ethanol and drop-in gasoline have different carbon intensities and use characteristics, they must be disaggregated to effectively model the fuel portfolio.

After consultation with stakeholders, we decided to assume that ethanol blended into gasoline or gasoline substitutes up to the blend wall level would be processed by the model first, effectively giving it the first cut of potential gasoline substitute volumes. Any residual after ethanol blending was assumed to be a drop-in gasoline substitute and the substitutes were, themselves, assumed to be blended with ethanol. Predicting which of the several technological pathways will supply this gasoline substitute is beyond the scope of this report, however we did identify some key performance characteristics that any substitute must possess.

To determine aggregate ethanol volume, we first estimated the amount of ethanol needed to blend into petroleum gasoline up to the blend wall, which is 10% through 2030 and 15% thereafter, plus an additional percentage point to reflect the small amount of E85 or other high-ethanol blends consumed at present. We also assumed that ethanol would be blended into any drop-in gasoline substitutes at the same level, though additional research into operational characteristics of such drop-ins is needed to confirm whether this would be the case.

Once an aggregate volume of ethanol was determined, it needed to be distributed between the various types of ethanol potentially available to the California market over the time period in this study. We disaggregated the ethanol pool into the primary types—starch, sugar, and cellulosic. Starch ethanol represents corn, and to a lesser extent, sorghum ethanol, which constitutes the overwhelming majority of ethanol now consumed in California. Sugar ethanol represents that made from waste sugars, such as bakery waste or molasses, as well as sugarcane ethanol, which is largely imported from Brazil. We assumed a very small amount of domestic waste-sugar ethanol being consumed typically. Brazilian sugarcane ethanol would only be consumed in the event of a shortage of domestic starch ethanol, or as a short-term response to an unexpected and transient LCFS credit deficit. Cellulosic ethanol is currently sourced from only a handful of demonstration facilities, or in some cases, co-produced in very small volumes from corn ethanol facilities using processes to convert corn kernel fiber into fermentable sugars.

Carbon intensities for all three categories of ethanol were taken from *CCFF* for years through 2030, and reduced by a specified yearly percentage thereafter. U.S. starch ethanol producers have significantly reduced the carbon intensity of their product over the 10 years that the LCFS has been in effect, and there are several plausible routes for technological advancement to allow the gradual reduction to continue [414], [415]. Corn ethanol production facilities may also be an opportune location for low-cost CCS, which would be expected to reduce the CI of the resulting product by around 30 g CO_2e/MJ [416] Sugar ethanol played a minimal role in all fuel portfolios modeled in this report. Cellulosic ethanol carbon intensity is subject to significant uncertainty due in part to the wide range of production processes that can produce it. Even within a single technology pathway, there is substantial uncertainty regarding the likely CI of commercial-scale cellulosic ethanol. For the purposes of this model, cellulosic ethanol was assumed to have a carbon intensity equal to the “current technology, base” scenario for corn-stover based cellulosic ethanol from Murphy & Kendall (2015), and a 2030 carbon intensity equal to the “future technology, base” scenario from the same source, with intermediate years interpolated between the two [417]. After 2030, it declines by the user-specified annual percentage.

The model then assigned the ethanol demand to the various sources of ethanol according to lowest carbon intensity, which for most years meant sugar was chosen first, then cellulosic, then starch. Emissions and LCFS credits were then calculated based on the volumes and carbon intensities.

Under most scenarios, ethanol struggled to continue to produce LCFS credits after 2040, a characteristic common to many fuels in this study. See the Policy Implications section for more discussion on LCFS parameters in the later years of the period evaluated in this study. At present, ethanol is required as an oxygenate to improve the combustion performance of gasoline; absent the emergence of new engine technology or fuel blends this is likely to be true through 2045. Further research is needed to understand how fuel producers and engine makers will adapt to emissions-control regulation in a market that is shifting away from the use of gasoline. It is possible that ethanol producers may choose to exit the California market if there is no more incentive for their product or if they begin generating deficits rather than credits, though fuel distributors may choose to continue the use of ethanol as an oxygenate despite the deficits it generates. Further research is needed to determine likely ethanol carbon intensity trajectories, as well as the need for oxygenate in the engines likely to be in use in the late 2030s and beyond.

14.3.6.2 Biomass Based Diesel

As it does with ethanol, the TTM aggregates all liquid diesel substitutes into a single category. In practice, there are at least two different substitutes that have unique characteristics, biodiesel (BD) and renewable diesel (RD). Biodiesel is typically blended into conventional diesel at around a 5% rate, though there are some consumers of higher blends. As we did with ethanol, we assumed that this blending would continue as long as there was liquid diesel—petroleum or otherwise—to be blended in to. Similar to ethanol, the BD blended into petroleum diesel was calculated first, any residual volumes were assumed to be RD with BD blended in at the same level. Similarly to ethanol, the presence of a modest number of high-blend consumers led to the average blend level across the full diesel pool being a percentage point higher than the nominal typical blend (6% while B5 is the typical retail blend in California), and we assumed that this small amount of BD consumption above normal blending would continue.

There were no sub-categories of fuel considered beyond BD and RD. There are pathways being evaluated that could yield cellulosic diesel, we group them with RD and expect that some of the CI reduction for RD modeled in this study would come from the displacement of higher-carbon crop-based RD by cellulosic. As discussed in the Distillate Constraints section above, we limited total consumption of distillates, including BD and RD, to 1.5 billion gallons per year. Given the wide variety of alternative fuel technologies available in the MD and HD sectors, and the cost savings from electrified drivetrains, petroleum diesel was eliminated from the fuel pool by 2042 in the LC1 scenario and 2041 in the ZEV scenario.

14.3.6.3 Electricity

Electricity was the largest contributor to decarbonization in all of the scenarios that complied, or even approached, the 2045 carbon neutrality target. At the time of writing, we are awaiting final results from a spatial electricity dispatch model that will give us a more granular estimation of electricity carbon intensity through 2045, considering the effects of a massively expanded EV fleet, as well as a need for electrolytically produced zero-carbon "green" hydrogen. For this version of the model, a simple linear decrease from the current grid average electricity value, as assessed by CARB, to a zero CI grid in 2045 was used.

At present, EV charging credit generators have the option of using the grid average CI for generating credits or opting into programs that allow for additional credit generation. Light-duty vehicles can opt for incremental credit generation opportunities for Renewable Energy, which is defined as zero-carbon electricity above and beyond the state's existing commitments for generation, or opt for smart charging, which provides an incentive for charging vehicles at times of low electricity demand and higher renewable energy supply. At present, almost all EV credit generators that have opted into an incremental credit program have picked the renewable energy credit option. Heavy duty vehicles can opt for a EV credit generation pathway using renewable electricity under certain conditions or by smart charging. For the purpose of this model, all pathways are treated equally and referred to as "incremental credits." There is a limited amount of data available on the utilization of the renewable energy provisions, as well as HD charging at non-grid-average CIs. Less is available regarding the smart charging provisions. In the absence of a clear understanding of how smart charging provisions might impact charging behavior over the long run, they were omitted from this study. The electricity section of the model assumed that smart charging provisions would gradually grow to represent 95% of potential charging, though given the rapid decline in grid carbon intensity over the time horizon of this model, these provisions ended up making minimal difference in LCFS credit balances.

The LCFS allows non-road vehicles, such as fixed-guideway transit (e.g., light or commuter rail), carbon handling equipment, and shore-powering of ocean-going vessels to generate credits. Limited data is available on credit generation, so expected credit generation from these pathways was based on *CCFF*, with a user-specified growth factor for years after 2030. California's commitment to reducing emissions from goods movement will likely incentivize a significant transition from diesel to electricity for the cargo handling equipment and ocean-going vessel category, so further research is warranted to develop a more nuanced estimate of likely deployment.

14.3.6.4 Renewable Natural Gas

At present, both renewable and fossil natural gas can generate LCFS credits when used for transportation. Given the expected trajectory of CI targets, fossil natural gas will likely become a deficit-generating fuel by the middle of the 2020s. Due to this, and the rapid expansion of cost-competitive RNG supply, the majority of natural gas fueled vehicles procure RNG in order to take advantage of the LCFS incentive. We assume that this behavior will continue and fossil natural gas will play a minimal role after 2021.

At present, CARB differentiates between liquefied natural gas (LNG) powertrains and compressed natural gas (CNG) ones. To date, the vast majority of deployed NG vehicles use the CNG pathway, due to the energy burden associated with liquefaction of natural gas, as well as losses from evaporation of the cryogenic liquid once loaded onto a vehicle. To simplify the calculations in the NG module, we do not differentiate between the two powertrain types, essentially assuming all NG vehicles use CNG as opposed to LNG.

The balance of RNG modeling is described in Section 14.3.4.

14.3.6.5 Hydrogen

Hydrogen plays a limited role in the transportation system at present, but some TTM scenarios project a significant penetration of hydrogen fuel cell vehicles, especially into the long-haul HD class. To be compliant with a carbon-neutral transportation system, this hydrogen must be supplied almost entirely by very-low or zero carbon sources. The CI for this hydrogen was based on modeling performed for the California Energy Commission (CEC), and yielded hydrogen well below 5 g CO_2e/MJ by 2045.[413]

14.3.6.6 Advanced Biofuels and Sustainable Aviation Fuel

Estimation of sustainable aviation fuel (SAF) demand was described in the Distillates section (14.3.3). We assume, for the purposes of model simplicity, that SAF will have priority on available low-carbon lipid feedstocks, and our modeling indicates that the expected availability of these is more than sufficient to satisfy demands from intra-state aviation.

Advanced biofuels, for the purpose of this model, refer to drop-in gasoline substitutes. While there are many potential pathways, most are too early in their development to allow projection of future volumes or properties. Instead, we focus on two sources of drop-in gasoline substitute. First, naphtha, which can be made from renewable feedstocks as a co-product of RD or SAF production. This naphtha is assumed to be co-processed in existing conventional refineries at relatively low concentrations, displacing some petroleum from the broad gasoline supply. This represents a relatively small volume of total production.

The second source of advanced biofuel is described simply as “Renewable Gasoline” and used to fulfill gasoline-pool biofuel requirements in excess of ethanol as projected by the TTM. There are a number of plausible pathways by which this could be produced, and we provide a full discussion of them, as well as the policy options needed to support this production, in the Fuel Policy section of the report (9.4.4).

14.3.6.7 Projects

The LCFS allows a small number of “projects” to generate credits. These ultimately do not produce fuel but reflect emissions reductions in the life cycle of transportation fuels. Since they have limited impact on the 2045 fuel portfolio, these are modeled as simple linear projections of existing trends and contribute only to LCFS compliance. Infrastructure capacity credits are assumed to reach their maximum allowed amount by 2022 and phase out for EV fast charging in the late 2020s and for hydrogen dispensing in the early 2030s. Refinery efficiency improvements were assumed to provide half their maximum allowable amount of credit in the LC1 scenario and all others that comply with the 2045 carbon neutrality goal. They are assumed to reach their maximum amount in the BAU scenario since the persistence of petroleum as a transportation fuel provides a greater opportunity to recoup investments in credit generation.

14.4 Health Appendix: Health Impacts Analysis

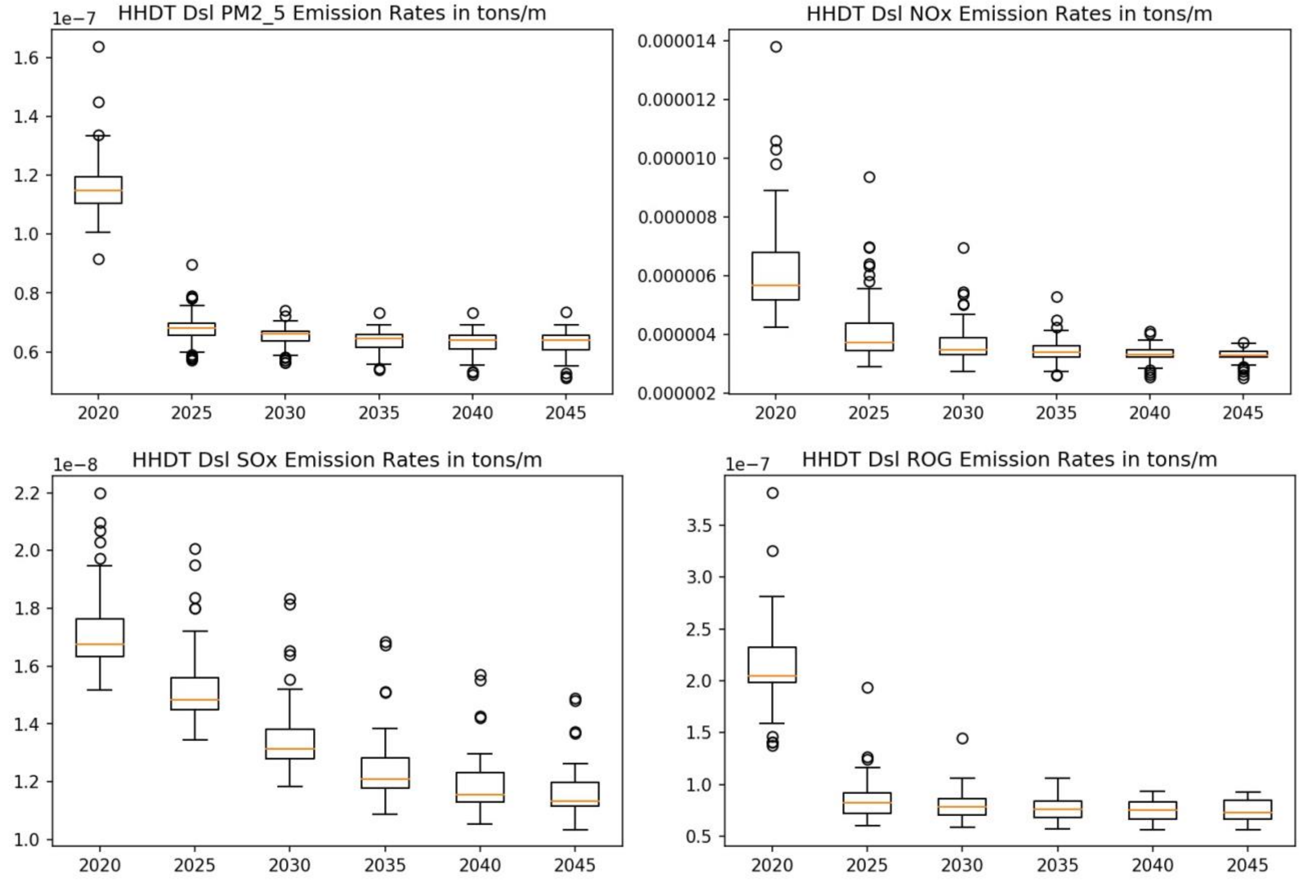

Figure 14.1. HHDT diesel emission factors for CA's 68 county–air basin sub areas

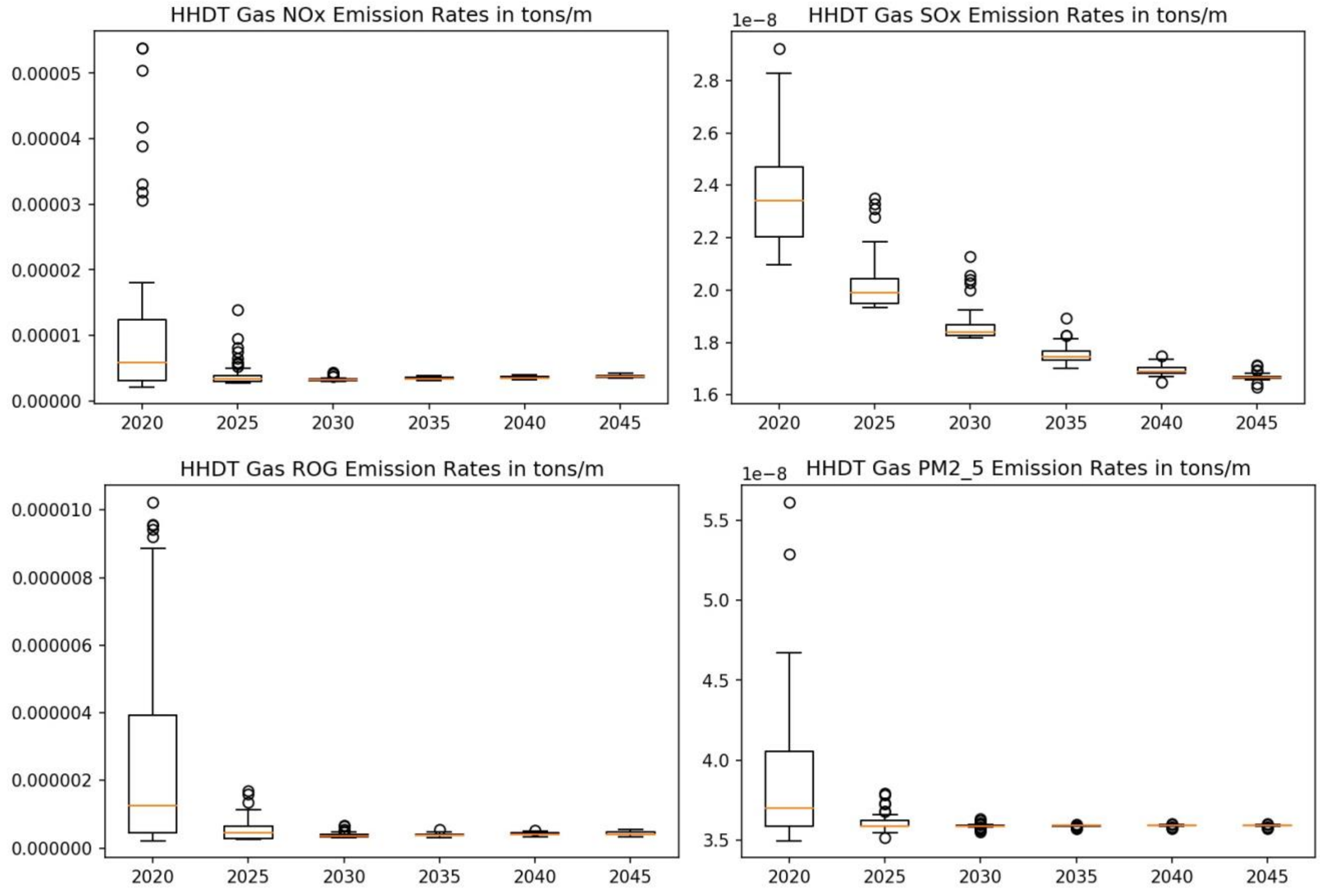

Figure 14.2. HHDT gasoline emission factors for CA's 68 county–air basin sub areas

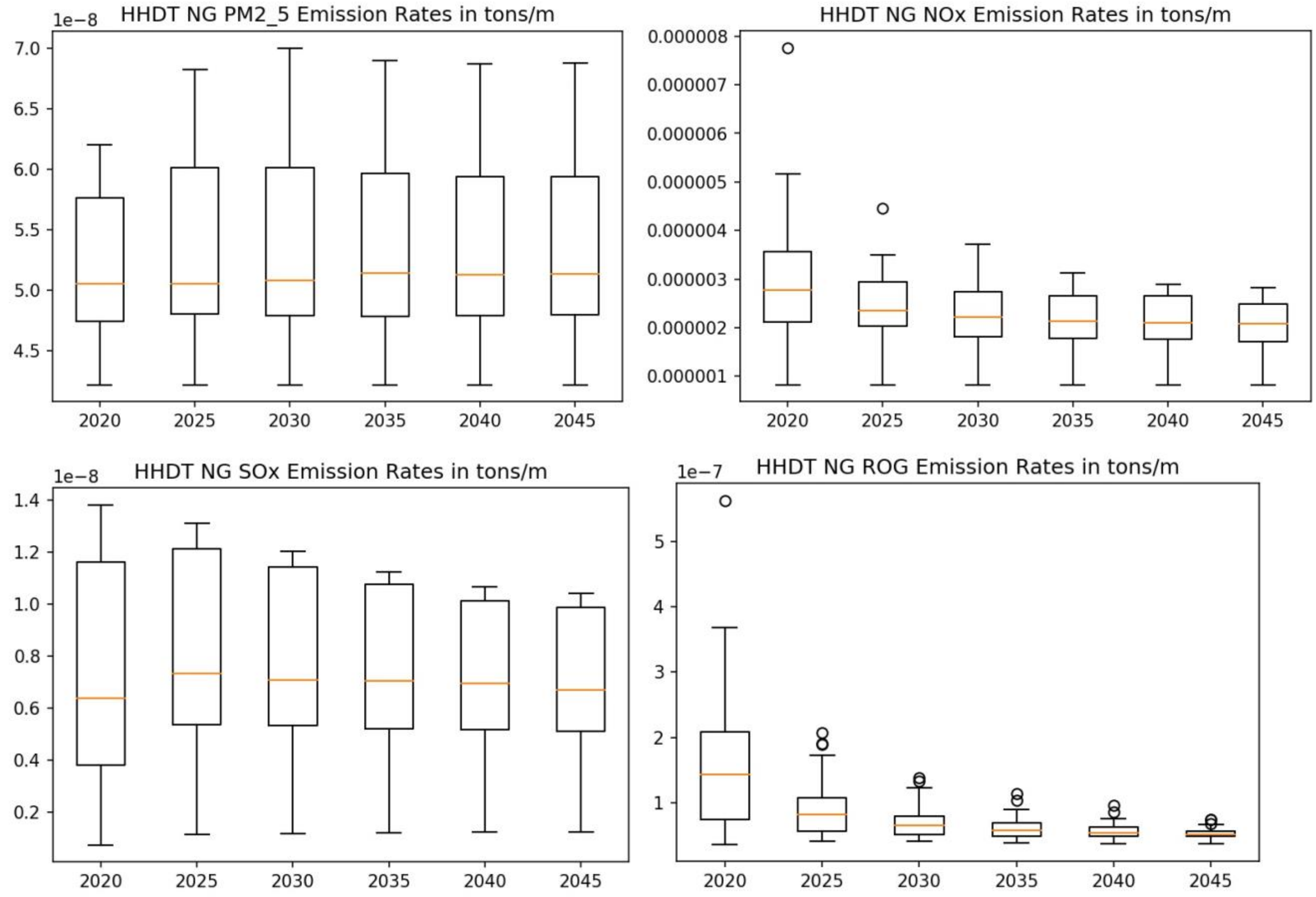

Figure 14.3. HHDT NG emission factors for County – Air Basin sub areas (36 observations)

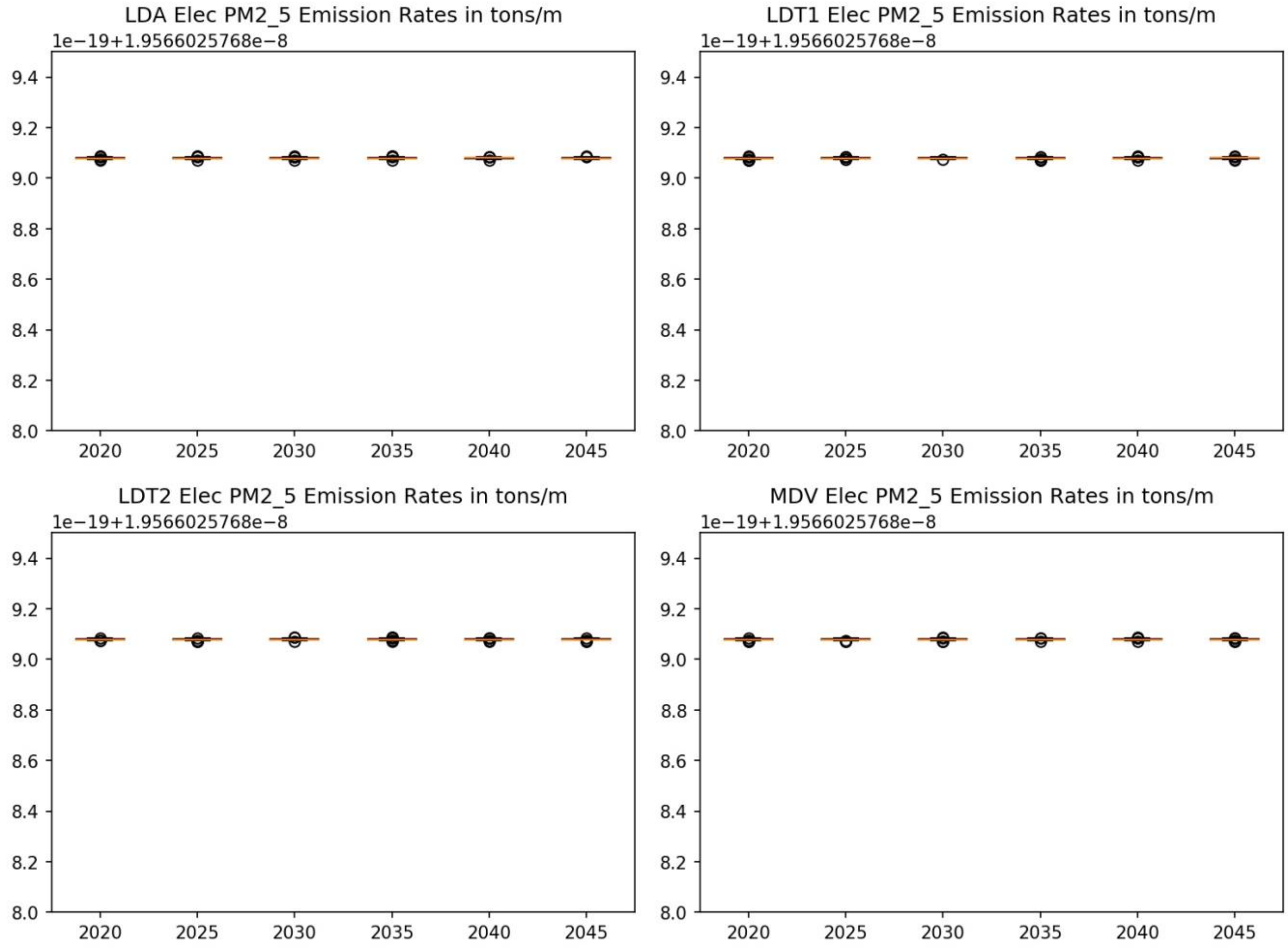

Figure 14.4. Passenger electric vehicle PM2.5 emission factors (68 observations)

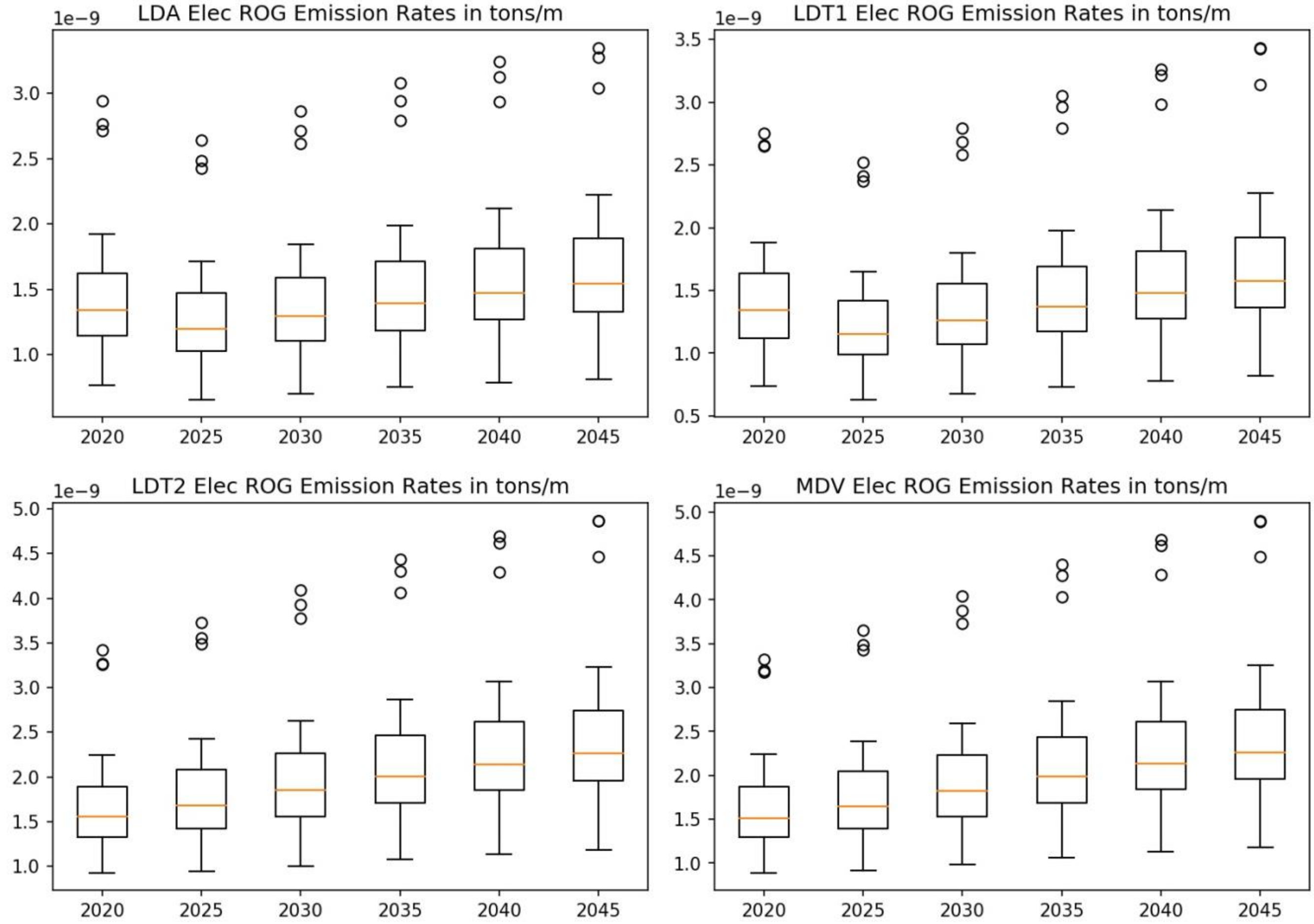

Figure 14.5. Passenger electric vehicle ROG emission factors for (68 observations)

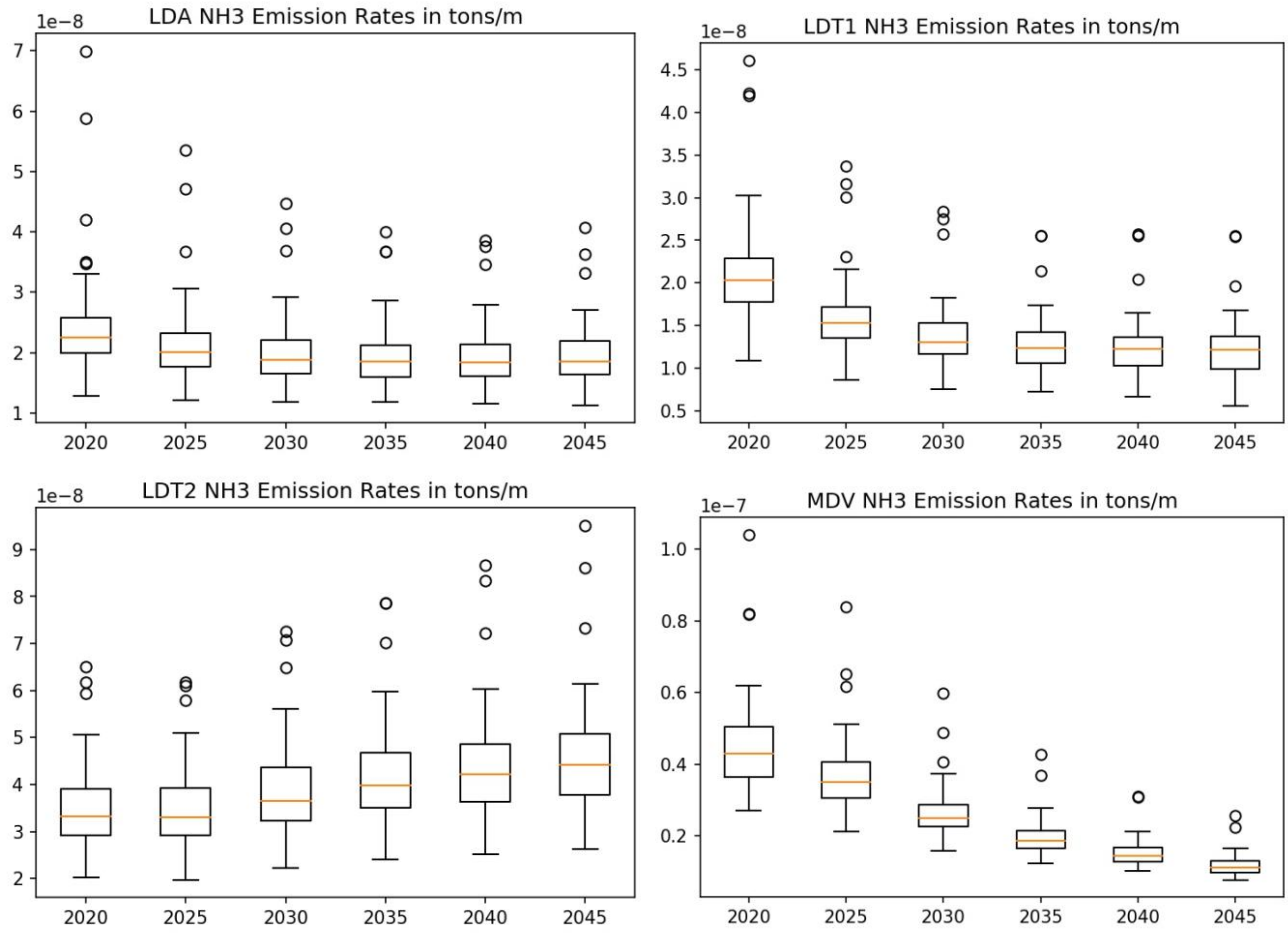

Figure 14.6. Light-duty Gas NH3 emission factors for County – Air Basin sub areas (68 observations)

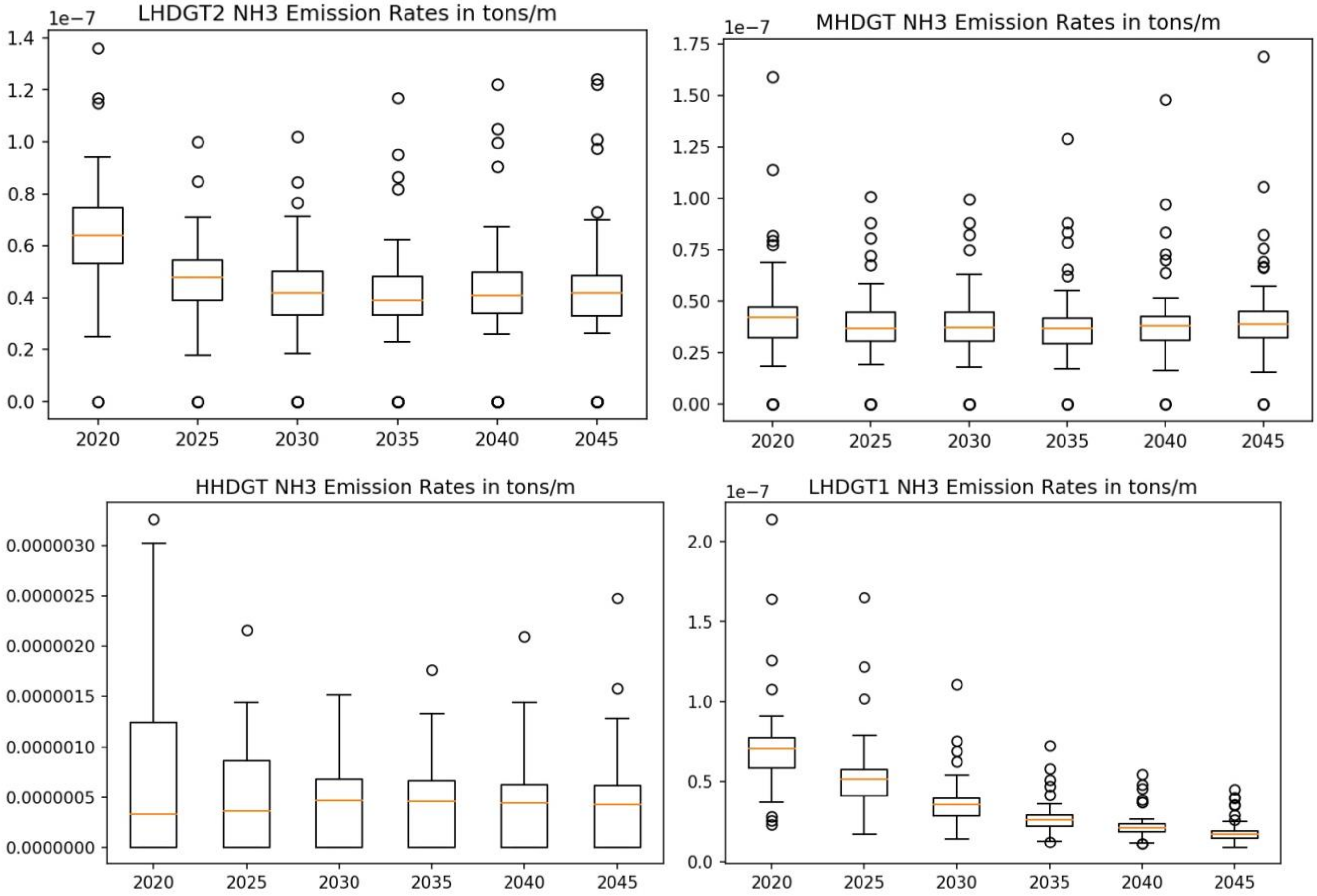

Figure 14.7. Heavy-duty Gas NH3 emission factors for 68 County - Air Basin sub areas

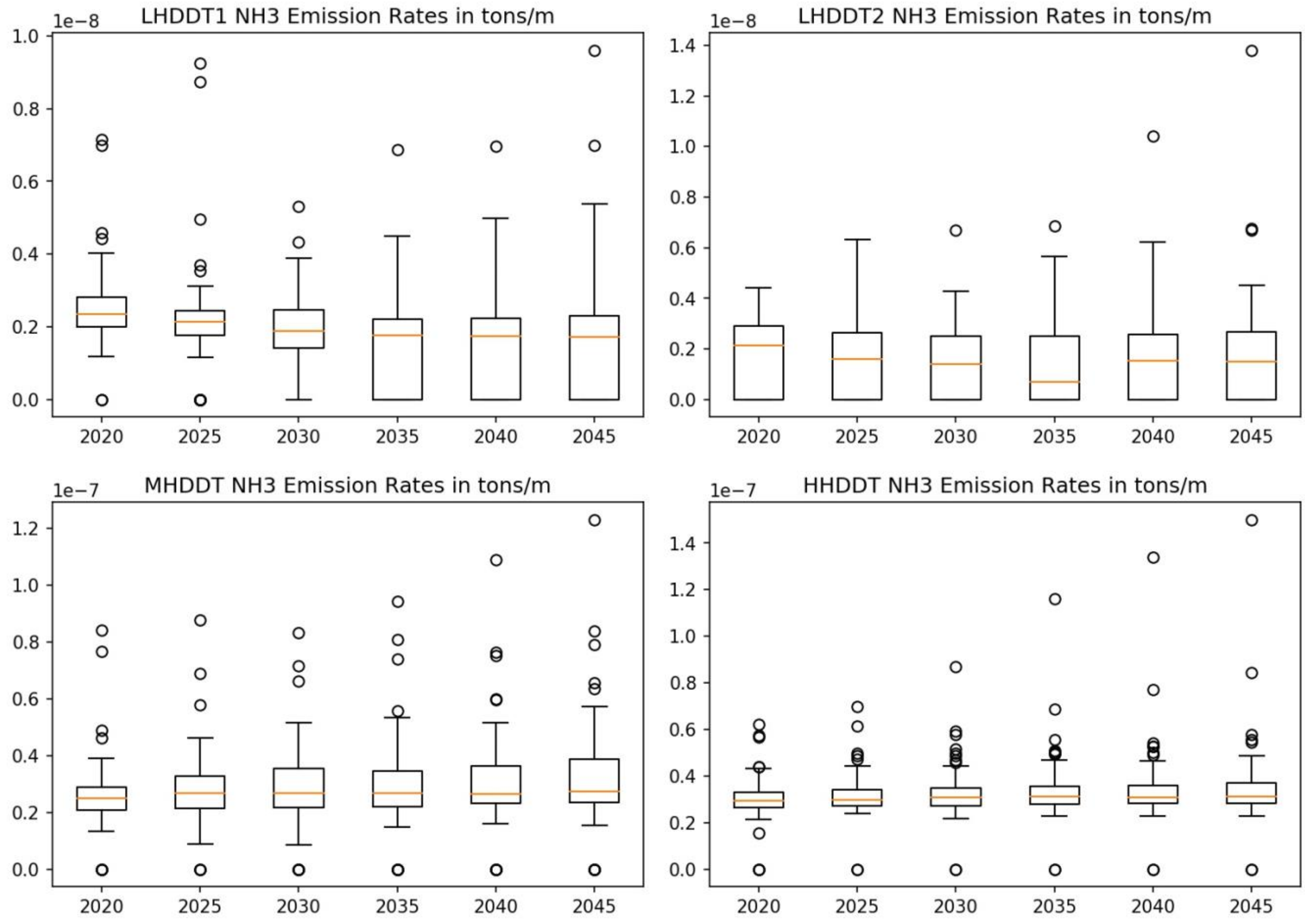

Figure 14.8. Heavy-duty diesel NH3 emission factors for 68 County–Air Basin sub areas

14.5Equity Appendix: Stakeholder Feedback

Table 14.43. Stakeholder feedback from workshop held on equity after Study 1 was released.

Stakeholder Feedback		
Key Issue	Description	Scenario
Cost distribution	Public health costs should not be externalized, and measures need to be taken to reduce barriers for low-income communities to adopt and utilize clean transportation, (e.g., subsidies, incentives). Communities that have been most harmed by fossil fuel extraction and use should be the first to benefit from policy change and clean technology.	Equity
Economic benefits	The producers and end-users of new technologies should both share in the economic benefits. Public-private investments in low-carbon or zero emission technologies and infrastructure should prioritize the public good and not solely benefit the for-profit technology and innovation companies.	Equity
Data driven policy and political willpower	Policymakers and elected officials must understand the severity of the climate crisis and operationalize the data to inform environmental policies.	Equity
Equitable implementation of new technology	The adoption of new technology needs to be paired with realistic, comprehensive, and equitable policies that do not disproportionately impact historically disadvantaged communities.	Equity
Expedited climate action	Expedited and more urgent policies are needed to reach emissions reduction goals. The public and policymakers alike, not just researchers, need to understand the necessity of attaining carbon neutrality.	Equity
Eliminate oil and gas dependence	Research should extend beyond carbon neutrality with the objective of achieving a zero emission transportation sector.	Fuels
Fuel options	Research and development needs to be undertaken to support a wide range of fuel options while also ensuring that dependence on alternative fuels (e.g., ethanol, biodiesel) is mitigated since many of these options can cause negative land-use changes and are not always carbon-neutral.	Fuels

Stakeholder Feedback		
Key Issue	Description	Scenario
Health benefits	Community health outcomes need to drive policies and practices, and disadvantaged communities need to receive an equitable share of these health benefits, (e.g., lower asthma rates, reduction in days of work or school lost, longer life span). Carbon neutrality research should integrate health findings with existing research on social determinants of health.	Health
Workforce development	A transition to a carbon neutral transportation system must include job protection, training, and local hiring.	Labor
Environmental benefits	Carbon neutrality research should prioritize air quality, water quality, and soil health benefits; natural resource protection; and biodiversity security. The transition to a low-carbon transportation system also needs to account for the full life cycle of new technologies and the e-waste that will be generated as a result.	LDV, HDV, VMT
Subsequent research	Research gaps that should be explored beyond this study include carbon reduction strategies, (e.g., carbon sequestration), beyond the transportation sector and account for the impacts of severe climate events on mobility and transportation, (e.g., natural and human-made disasters).	TBD
Accessible and efficient clean transit	Low-carbon or zero-emission options for personal vehicles, public transit, and active transportation should provide increased connectivity, affordable options, and reliability.	VMT
Robust infrastructure	Infrastructure investments need to support clean transportation choices, including ZEVs, public transit, and active transit.	VMT
Regional land use planning	Comprehensive land use planning needs to ensure connectivity within and between regions, and with priorities that support a reduction in VMT, including the reduction of sprawl, support of local supply chains, and attainment of a jobs/housing fit.	VMT
VMT reduction	The research should address VMT reduction across the board, not only with low-carbon or ZEV technology, but by also reducing emissions from internal combustion engine vehicles which will be on the road for the foreseeable future.	VMT

14.6Workforce Appendix: Key Contextual Factors Regarding the Model

In addition to the broad limitations of the IMPLAN model discussed in the workforce section, there are several model-related dynamics that influence the results presented in Section 12, particularly with respect to key trends and occupational labor figures:

1. *Adjustments for Inflation*: IMPLAN adjusts for inflation when computing employment numbers related to future expenditures. Consequently, employment generated from a given level of expenditures is deflated when examining periods many years into the future, even when considering similar or identical industries. These trends also reflect the tendency of industries to achieve greater worker productivity and other efficiencies over time that reduce the labor generated for a given level of expenditures over time.

   In the model results presented, this is especially notable when comparing employment generated in industries related to electric vehicles (EVs)– versus internal combustion engine vehicles (ICEVs). While the number of vehicles sold and total expenditures on new vehicles are similar in the respective peak years for these two sectors, the peak of new EV sales occurs many years in the future; thus, the model calculates peak employment in this area as being noticeably lower, both per unit of expenditure and in overall magnitude, than that for ICEV-related sectors.

2. *Simplified Occupational Breakdowns*: The IMPLAN occupational matrix used to disaggregate job totals within industries into figures for specific occupations uses a static set of proportional values to calculate an industry's breakdown. These values are national, weighted averages of industries aggregated into sectors under the IMPLAN industry categorization scheme. Thus, the breakdowns do not necessarily reflect the actual occupational makeup of industries in California and are susceptible to aggregation bias.

   For instance, if Industry Sector A is made up of 10 industries and is nationally composed of 50% Occupation X and 50% Occupation Y across those industries, applying the matrix to a job total for any industry within Industry Sector A will always split those jobs between Occupations X and Y, 50-50, regardless of what overall jobs figures are for that specific industry in California. Additionally, any future changes in occupational breakdown for that industry or the industry sector are not captured.

   This presents a challenge in assessing the accuracy of occupation-specific job estimates many years into the future. Again, the case of employment generated from new battery electric vehicle (BEV) sales is a relevant example. As mentioned, overall estimated employment generated by a given level of expenditures decreases in this sector over time as the model compensates for inflation and increasing labor productivity. Applying the occupational matrix produces estimates that split the final job numbers across occupations according to fixed proportions. It is unable to account for the possibility that employment in occupations may respond differently to changing conditions over time (e.g., that manufacturing jobs experience an outsized decline compared to other occupations due to productivity gains). Additionally, the model cannot recognize the potential for employment in certain occupations to be more responsive to variables other than total expenditures—for instance, the possibility that retail vehicle sales employment fluctuates more in response to numbers of vehicles sold than vehicle purchases themselves.

3. *Differences in Classification Schemes versus Baseline Data*: comparing projected employment figures versus baseline data for specific occupations is made difficult by mismatched classification schemes. The categories for employment utilized by our baseline data sources—the Quarterly Census of Employment and Wages (QCEW) and data from the Occupational Employment Statistics (OES) program, both managed by the U.S. Bureau of Labor Statistics (BLS)—are not identical to those used within the IMPLAN occupational matrix. This means that in some cases, figures related to certain fields of employment produced by the model may appear to be greater in magnitude than their closest baseline categorical counterpart, due to inclusion of a broader array of workers within that number.

   Additionally, IMPLAN may account for jobs in particular fields that are either not captured within BLS surveys or are classified in such a way that they are accounted for in categories not necessarily reflective of the occupation. Regarding the former, a key example is that the model estimates employment for mechanics based on expenditures derived from fleet size, vehicle miles traveled (VMT), and per-mile maintenance cost. Unpaid, non-professional maintenance performed on a vehicle by the owner would be reflected in IMPLAN's job totals while not appearing in BLS data. In the case of the latter, IMPLAN would capture hours performed maintaining vehicles by an employee of a private fleet, even if these tasks are not the employee's primary responsibility. In both cases, the modeled job numbers would exceed those reflected in baseline BLS figures.

4. *Limited Ability to Account for Labor in Nascent Industries*: IMPLAN uses a static set of relationships to quantify employment generated by a given industry. However, such established frameworks do not exist in the case of certain nascent industries relevant to this study, such as the operation of public DC fast charger stations for BEVs. In such cases the workforce impact of these firms are generally modeled as their closest analogue.

   However, this creates the possibility of the model significantly underestimating employment in certain occupations. For instance, the model results indicate that consumption of electricity as a transportation fuel creates a meager number of retail sales jobs, meaning that most of the gross losses of gasoline station jobs would manifest as net losses. While this outcome is likely to be realized to some extent due to the expansion of home and workplace charging, it is possible that the tens of thousands of public DC fast charger stations could generate new employment in a business model that resembles that of gasoline stations. The potential scale of such impacts is highly uncertain, depending on factors such as the number of chargers at a station, the prevalence of automation, and the propensity of linked businesses to co-locate. Regardless, these jobs are not reflected in the model's totals because this industry does not exist in its current framework.

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